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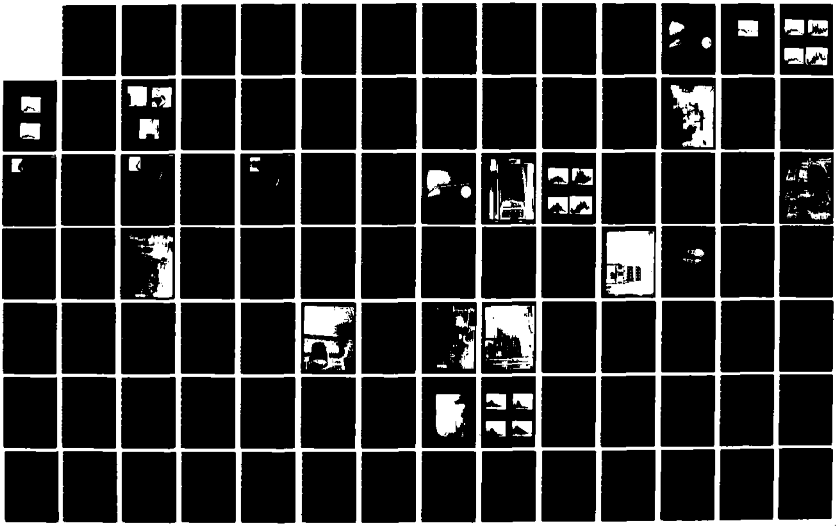

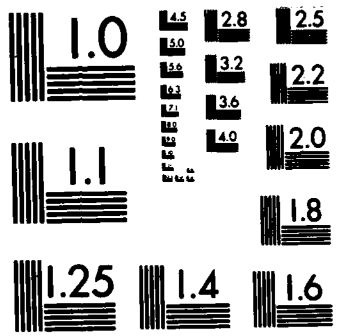

MICROCOPY RESOLUTION TEST CHART
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A CALIBRATED, BROADBAND ANTENNA FOR PLASMA RF EMISSION MEASUREMENTS BELOW 1 GHz*

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A constant impedance, constant aperture antenna can make possible broadband plasma RF emission measurements which yield relative and absolute power levels. However, good technique, such as that described by Heald and Wharton [1], must be followed for the immersion of such an RF probe into plasma radiation.

We have used a complementary conical spiral antenna, similar to that described by Rumsey [2], to observe plasma RF emission over the frequency range $100 \leq \nu \leq 1200$ MHz. The RF emission was emitted by a modified Penning discharge as described by Roth [3] and Roth, Hayman, and Pastel [4]. The RF emission from the discharge typically exhibits harmonic structure over a broad frequency range, necessitating a broadband antenna with a flat frequency response curve to allow detailed spectral analysis.

The antenna consists of two metal strips of approximately uniform width wound helically on a cone made of Lexan plastic. Since the antenna is a balanced network, a balun is employed to make the transition to a 50-ohm coaxial line. The antenna feed methods is critical in maintaining a uniform

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impedance network. Neglecting stray transmission line effects, the probe circuit for the frequency range $100 \leq \nu \leq 500$ MHz is 50 ohms due to the spectrum analyzer, paralleled by 291 ohms due to balun magnetization; the combination is fed by a 144 ohm probe aperture (see Fig. 1). Above 500 MHz, the balun seem to behave nonuniformly and requires further fine tuning to achieve a satisfactory frequency response and an accurate calibration over the frequency range from 500 MHz to 1.0 GHz. Below 100 MHz, it is not clear that the antenna remains properly immersed in the plasma radiation under present laboratory conditions.

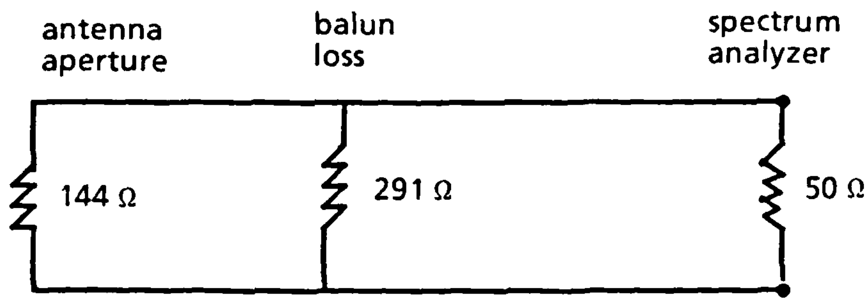


Figure 1

REFERENCES

1. M. A. Heald and C. B. Wharton, Plasma Diagnostics With Microwaves, Krieger Publishing, New York, 1978.

2. V. Rumsey, Frequency Independent Antennas, Academic Press, New York, 1966.

3. J. R. Roth, Modification of Penning Discharge Useful in Plasma Physics Experimeents, RSI, 37 (1966), 1100-1101.

4. J. R. Roth, P. W. Hayman, and R. L. Pastel, A Paired Comparison of High Frequency RF Emission from Two Configurations of Electric Field Dominated Plasma, Proc. 1982 Int. Conf. on Plasma Physics, Goteborg, Sweden.

Introduction

Log spiral and log periodic antenna structures can be constructed to operate over multioctave frequency bandwidths.[1] The log spiral and other types of spiral antenna are exploited in broadband radar technique and in direction finding.[2] Their constant impedance and uniform aperture due to complementary structure make them well suited to broadband, far fiel RF plasma emission measurements.

A complementary antenna structure is one in which there is equal share of conductor and dielectric area on the radiating surface (see Figure 1). The impedance of such a structure is theoretically one half that of free space, 188 ohms. In practice an impedance of about 160 ohms is found.[3] A major limit in exploiting full bandwidth of a given structure is the matching of the antenna impedance to that of (usually) a 50 ohm system. That is, when using a spiral antenna for plasma diagnostics the uniform impedance of the antenna and the uniformity of pattern shape must be maintained over large bandwidths, otherwise antenna resonances will introduce false RF spectral responses, and yield distorted measurements.

Low frequency limits of spiral antennae are usually set by the maximum diameters of the structures; presumably one quarter of a longest received wave length.[3] For low frequencies, say 50 MHz, a structure at least 1.5 meters in diameter is required. Most laboratory conditions make this impractical. However by suitable end loading, low frequency limits of smaller structures can often be extended.

We have developed two spiral structures which operate satisfactorily over the frequency range 50 to 1000 MHz and have essentially uniform apertures from 200 MHz to 900 MHz.

I. Conical Spiral

We have constructed a complementary conical spiral antenna 83.9 cm long with a base diameter of 35.5 cm and tip diameter of 1.3 cm; with two uniform lead alloy strips, 1.27 cm in width, wrapped on a Lexan cone. Approximately 17 cm from the tip, a transition section is used to reduce the 1.27 cm strip width to .16 cm. Inside the apex of the cone, a 4 to 1 UHF-VHF Balun is used. A 47 ohm resistor is placed in series with each arm of the antenna to facilitate an improved match. Tungsten wool surrounds the balun to shield the latter and also to help dissipate reflections on the antenna structure. The spiral is wound for right hand polarization.

Planer Spiral Antenna:

A two turn two arm planer log spiral 35.6 cm in diameter, constructed using printed circuit technique is shown in Figure 1. High frequency P.C. board was used and the same type of 4 to 1 balun as above was used for matching. The planer spiral is wound for left hand polarication, and is fitted with a cavity backing. The cavity is fitted with layers of tungsten wool which isolate the antenna from backside reception and from interaction with its balun feed network. The careful placing of tungsten wool allowed extension of this antenna to low frequencies.

Calibration:

Initial calibrations of both antenna were done in order to discount as much nonuniform impedance response as possible. An HP 8554 spectrum analyzer in conjunction with an HP 8444A Tracking Generator as its swept sources, were used to monitor the swept return loss. A 1641 GR Swept Reflectometer was modified to act as a broadband diretional cou ple r to sample reflected power.

Figure 2 shows return loss for the conical spiral. Resonances can be observed at various frequencies and are considered as follows:

At 200 MHz, return loss is -10 log $|\Gamma|^2$ = - 22 dB, i.e. 99.2% of the power captured by the antenna will be delivered to a 50 ohm receiver. At slightly off 200 MHz, return loss is now - 6dB, or only 75% of the captured radiation will be transmitted to a 50 ohm receiver. In terms of dB, this is only a 1.25 dB induced resonance. This can be seen in the fine structure of figure 6.

From arguments similar to the above a limit of -6 dB was set for an acceptable $|\Gamma|^2$. For subsequent power measurements an average -9 dB was taken for the conical spiral tramission efficiency; ε = 88%. Figure 3 shows the swept reflection coefficient for the planer spiral. This antenna has a very nice response with an average 6 dB return or ε = 75%. Only one large resonance is evident at about 125 MHz. It is noted that considerable effort was required to obtain response figures 2 and 3.

After the antenne impedances were matched, their response patterns were compared. RF emission from a Modified Penning Discharge (see paper 3R3) was adjusted for broadband output. This spectrum is shown in figures 4 thru 7. Although amplitudes are different, the general shapes of the

emissions in figures 4 and 5 are quite similar. Enlargement in figures 6 and 7 shows very good agreement of the harmonic structure of the emission. Fine structure in $|r|^2$ of the conical spiral (figure 2) now shows up as fine structure on figure 6.

Effective Apperture:

The effective aperture of an antenna is an area that corresponds to the effective capture area for incoming radiation. This area is dependent on the antenna structure as well as polarization of the incoming radiation and reflections.

In order to calibrate the effective aperture, the broadband radiation pattern of the plasma from 700 Hz to 1200 MHz was investigated using a ridged horn terminated in a thermistor power meter. In this frequency range the plasma was found to behave as a cylindrical radiator. A standard half wavelength dipole taken from an Empire Devices field strength set was then used to determine that RF radiation was linearly polarized with the E plane parallel to the static B field of the plasma. This agreed with polarization indicated by the ridged horn.

Figures 8 and 9 show plasma emission detected by the conical spiral and planer spiral antennae respectively for effective area calculation. By the procedure employed, detected power flux in a given bandwidth, using a standard half wave dipole, was compared to power detected by each spiral antenna.

The effective aperture of a half wavelength dipole was taken to be

$A_{eff} = 0.13\,\lambda^2$

Power measurements from 100 MHz to 1000 MHz in 100 MHz intervals where taken for each the dipole and the two spirals. RF power captured by each antenna was measured over a 10 MHz bandwidth about the center frequency with a 300 KHz sampling bandwidth. For the dipole a polarization and scattering loss of 1 dBm was added to these measurements and for the spirals 3 dBm was added to account for the linear polarization mismatch to a circularly polarized antenna. Cable losses were also considered as was $|\Gamma|^2$ measured at each frequency for each antenna. Effective aperture as a function of frequeny for the three antennae is shown in figure 10.

A distance correction was also included in calculating the effective apperature. We tried to maintain a spacing of at least one wavelength between antenna. This is slightly violated at 100 MHz. Do to this spacing however the dipole and the spirals were not at the same distance from the plasma. This correction was taken to go as 1/r rather $1/r^2$ do to the laboratory radiation environment.

Results:

The plasma emission to be detected by these antennae is usually inthe frequency range of 100 MHz to 1000 MHz with the peak of the emission envelop from 300 MHz to 900 MHz. Consequently we take from figure 10 a mean effective aperture for each antenna as:

A_{eff} (Conical Spiral) = 633 cm^2

A_{eff} (Planer Spiral) = 143 cm^2

From figures 2 and 3 we take a mean power transmission efficiency for the two antennae as

ε_m (Conical Spiral) = 88%

ε_m (Planer Spiral) = 75%

These results in conjunction with polarization mismatch and cable losses are what we need for net rF power measurements of the plasma discharge (see paper 3R3).

The effective aperture's can be compared to the actual antenna surface's of

Area conical spiral = 4682 cm^2

Area planer spiral = 993 cm^2

Thus, effectie aperture of the conical spiral is 13.5% of its total surface area where as effective aperture of the planer spiral is 14.4% of its total area.

Conclusions:

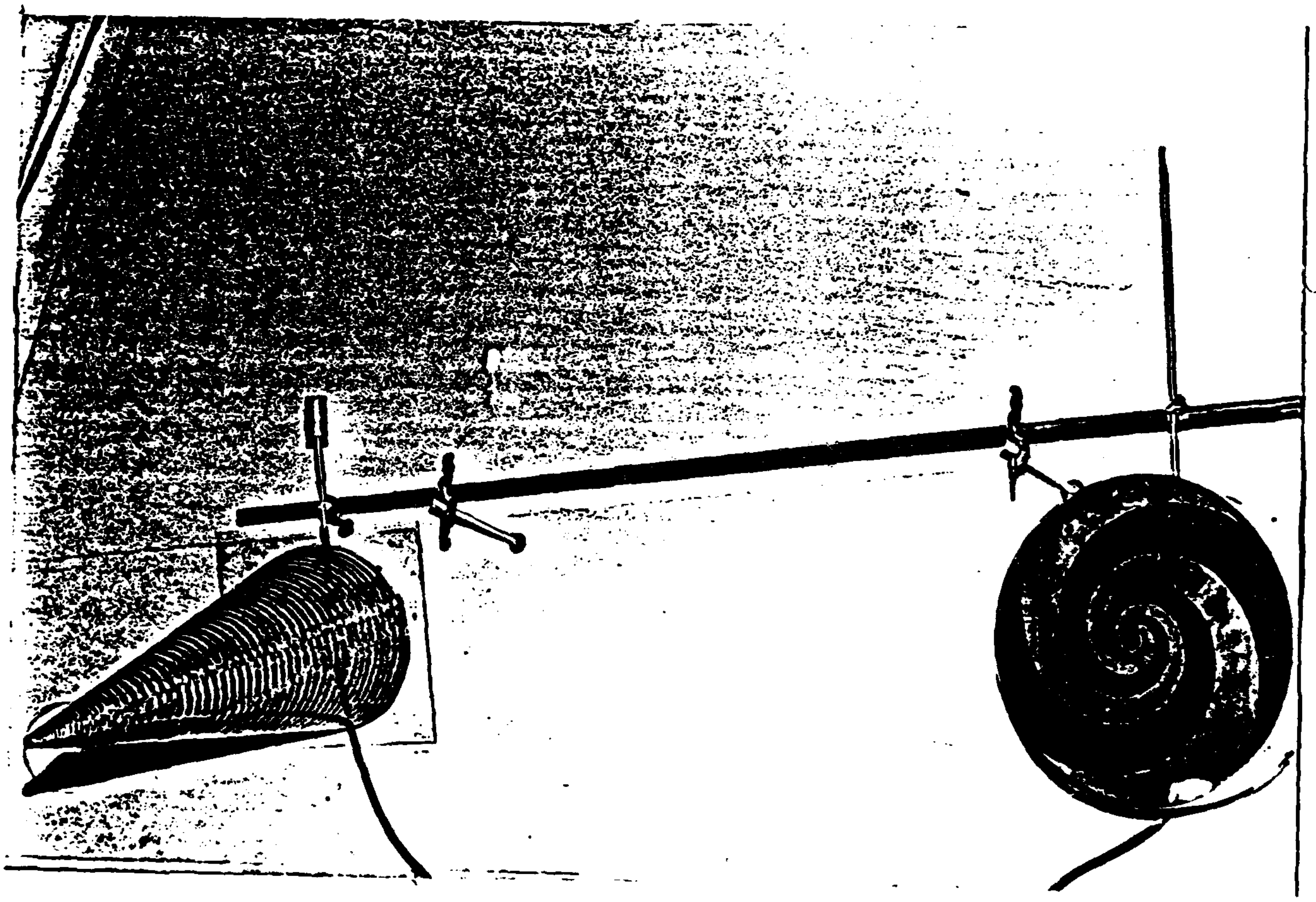
We have developed two spiral antennae which operate over the frequency range of 50 MHz to 1000 MHz and which can be used for detailed RF spectral data analysis of broadband far field power fluxes. The right hand and left hand polarizations of the two antennae allow additional information of the plasma's emission.

The calibration of the antenna has allowed us subsequently to determine local R.F. power flux measurements to within an order of magnitude.

REFERENCES

1. V. Rumsey, " Frequency Independent Antennas, Academic Press." New York, 1966.
2. J. A. Mosko, "An Introduction to Wideband Two-Channel Direction-Finding Systems" Microwave Journal Feb., 1984.
3. Theile, Stutzman, "Antenna Theory and Design", Wiley, 1981.

FIGURE 1



CONICAL SPIRAL

PLANER LOG SPIRAL

FIGURE 2

REFLECTION COEF. - CONICAL SPIRAL

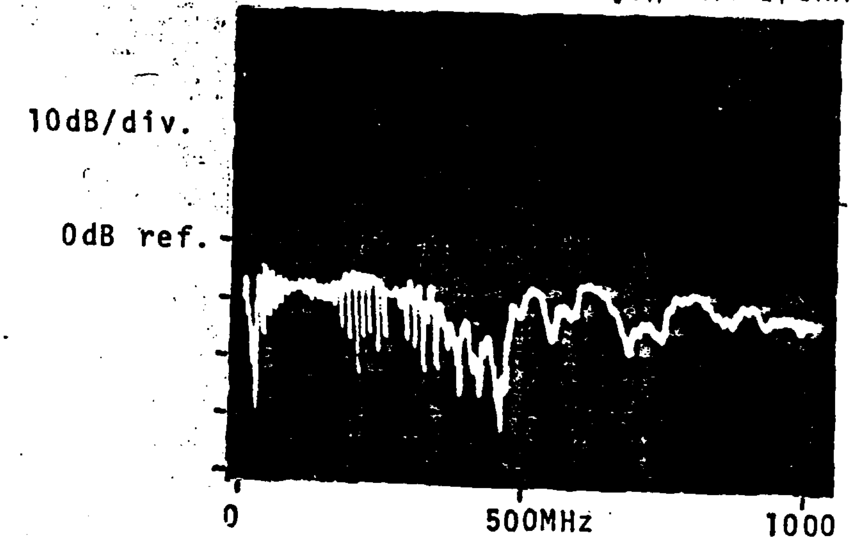


FIGURE 3

REFLECTION COEF. - PLANAR SPIRAL

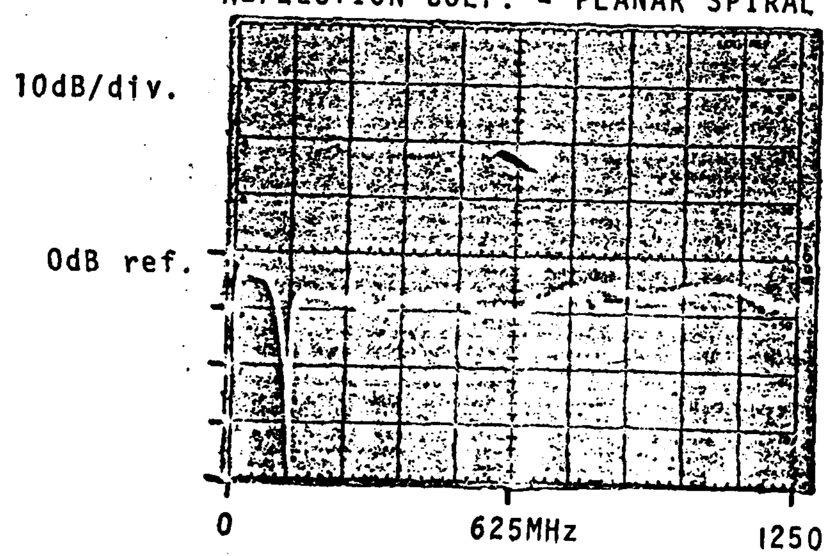
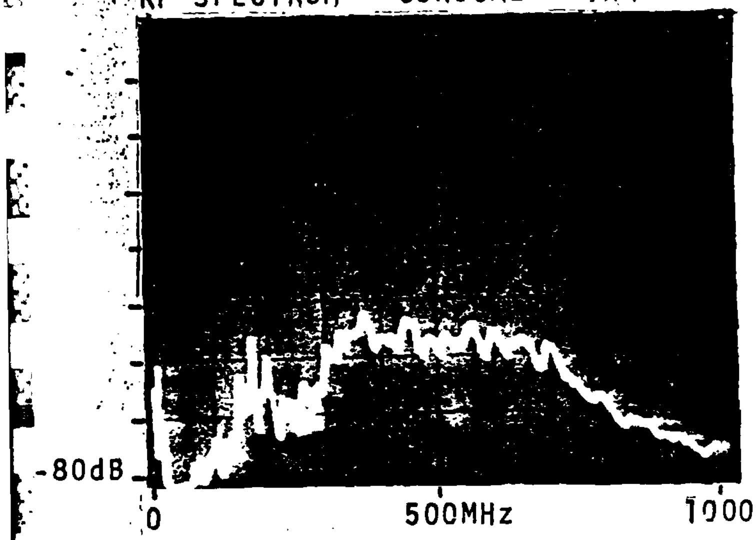
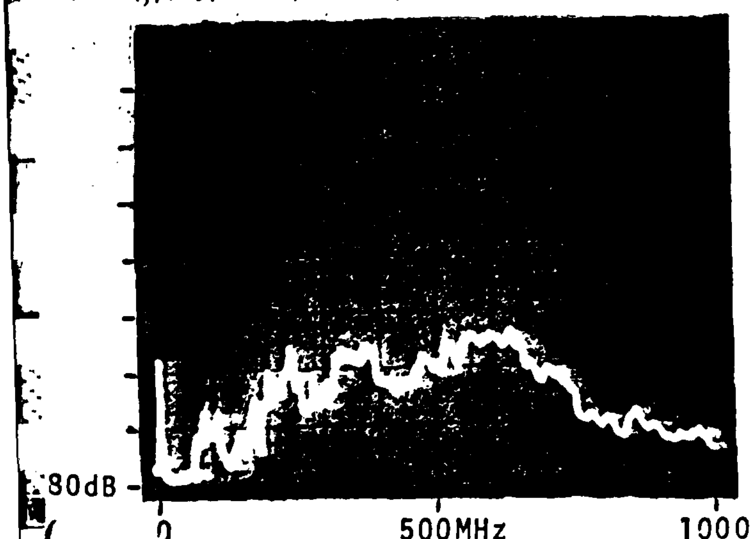


FIGURE 4
RF SPECTRUM - CONICAL SPIRAL



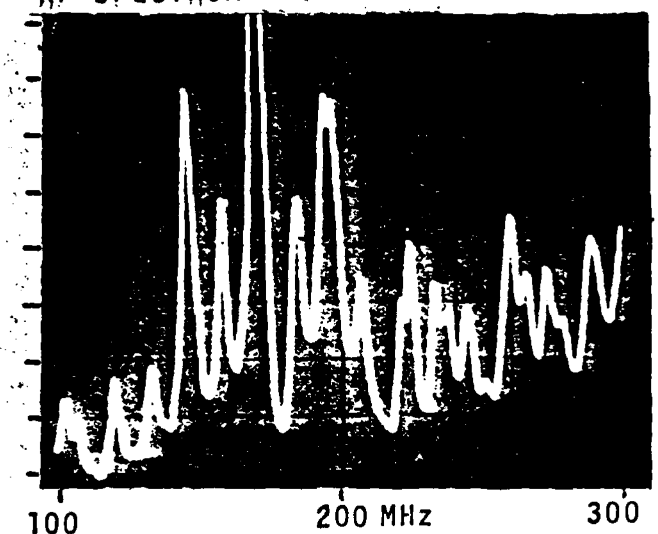
10dB/div for above

FIGURE 5
RF SPECTRUM - PLANAR SPIRAL



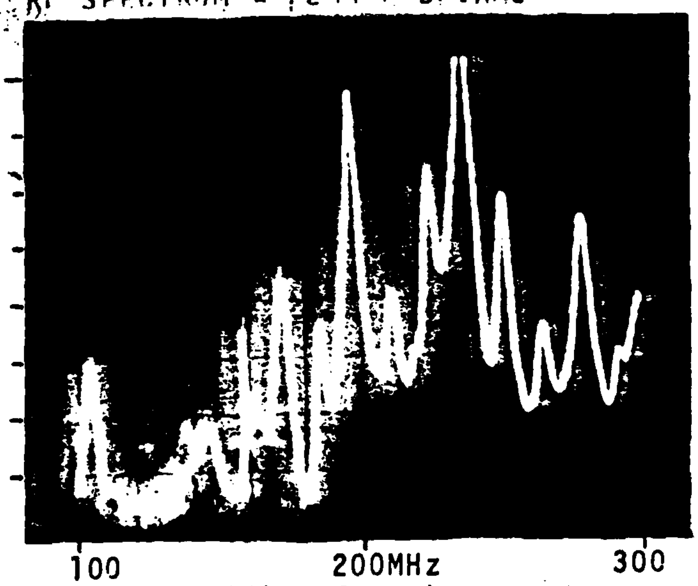
10dB/div for above

FIGURE 6
RF SPECTRUM - CONICAL SPIRAL



0.1mV/div for above

FIGURE 7
RF SPECTRUM - PLANAR SPIRAL



20uV/div. for above

RF SPECTRUM FOR APERTURE CALIBRATION

PLASMA CONDITIONS:

ANODE VOLTAGE	3900 volts
ANODE CURRENT	64 mA
He gas Pres.	5.2×10^{-5} torr
Max B field	0.33 tesla

FIGURE 8
CONICAL SPIRAL

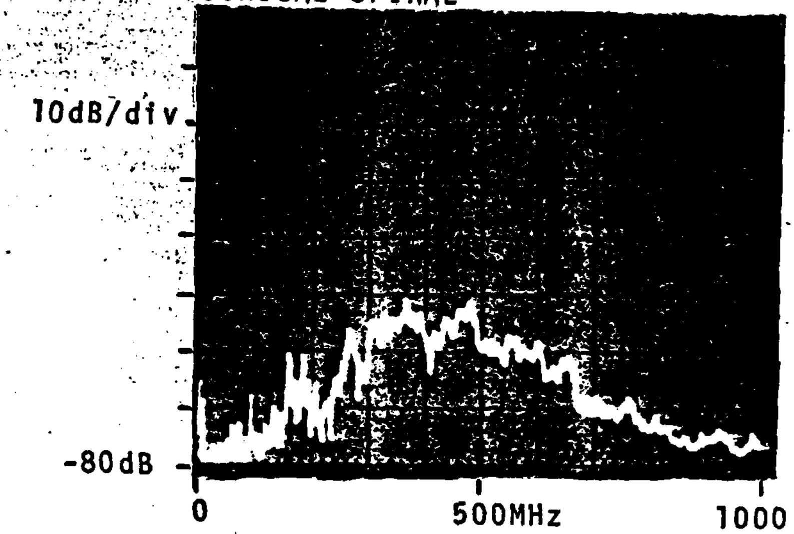
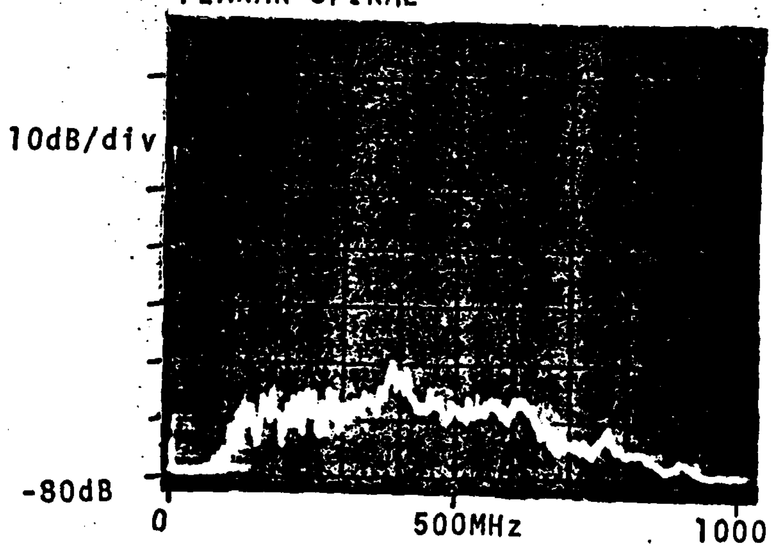
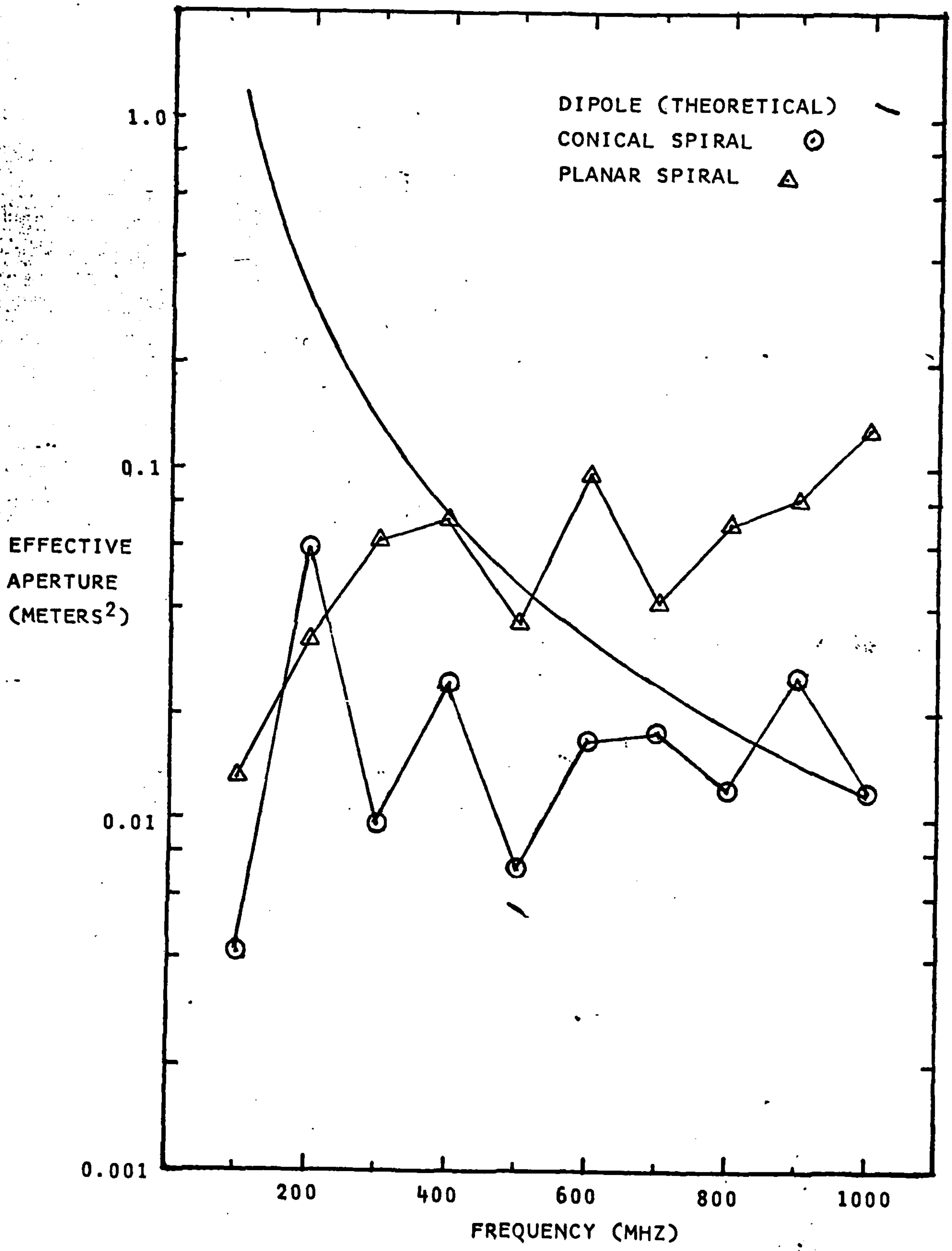


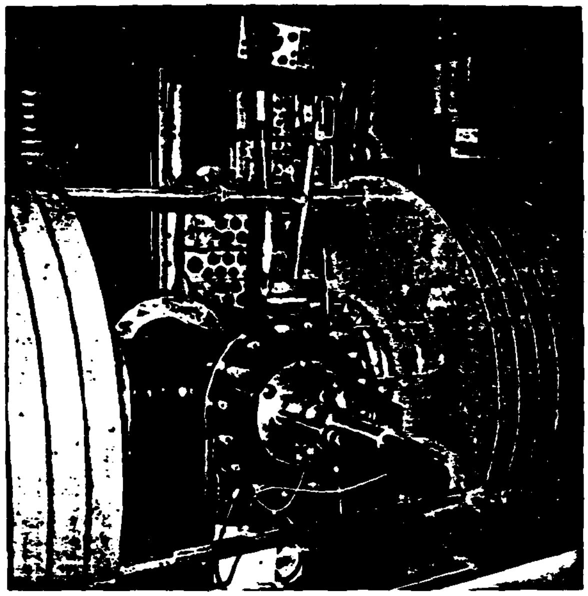
FIGURE 9
PLANAR SPIRAL

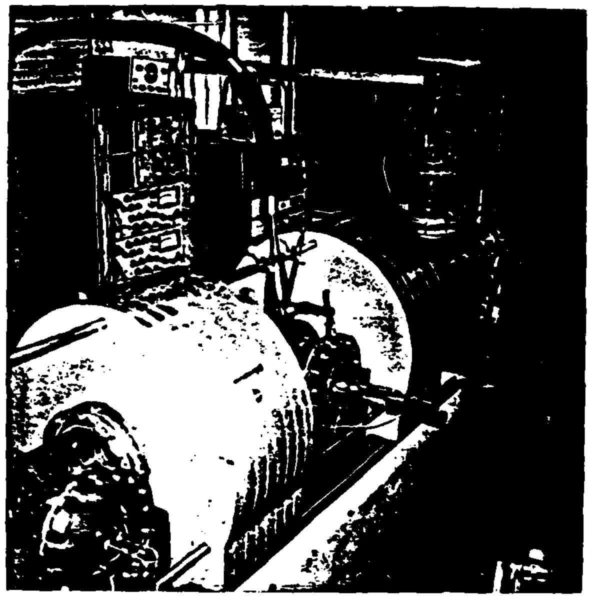


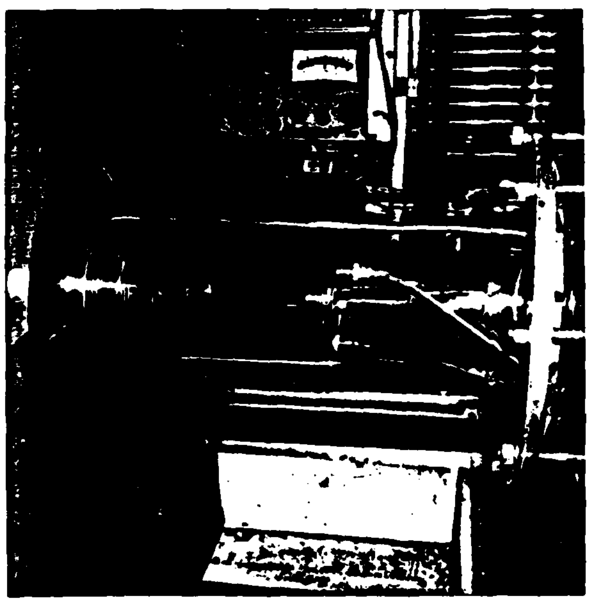
GRAPH 1


DIPOLE (THEORETICAL)
CONICAL SPIRAL
PLANAR SPIRAL
1.0
0.1
0.01
0.001
EFFECTIVE APERTURE (METERS^2)
200
400
600
800
1000
FREQUENCY (MHZ)

THE MODIFIED PENNING DISCHARGE







ENERGY ANALYZER

CORRELATION OF RF EMISSION, PLASMA WAVE PROPAGATION, AND PLASMA TURBULENCE IN CLASSICAL AND MODIFIED PENNING DISCHARGES

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Abstract

We have taken data from two versions of the Penning discharge which contain highly turbulent, electric field dominated plasma with densities up to $3 \times 10^{10}/cm^3$. Auto and cross-correlation techniques were used to obtain information about the turbulence and wave propagation in this plasma from capacitive probe and microwave scattering signals.

1. Introduction

We have performed a paired comparison experiment on steady state plasma created in classical [1] and modified Penning discharges [2] in uniform and magnetic mirror geometries, respectively. Our classical Penning discharge consists of a uniform magnetic field up to 0.40 Tesla, and our modified Penning discharge of a 5.7:1 magnetic mirror ratio with a maximum magnetic field on the axis up to 0.40 Tesla. The electrons are trapped in an axial electrostatic potential well, and in both cases form a plasma about 10 cm in diameter in the midplane. The electron population forms two interpenetrating beams in the background plasma which give rise to the geometric mean and other plasma instabilities [3,4]. These plasmas support high levels of electrostatic turbulence, axial electric fields up to several hundred volts per centimeter, and emit broadband electromagnetic radiation over the frequency range from below 1 MHz to more than 2 GHz [4,5,6]. These plasmas draw anode currents up to 0.5 amps at up to 7.0 kV anode potential, and characteristically have densities that range from below $10^8/cm^3$ to above 5×10^{10}. Characteristic electron kinetic temperatures observed with Langmuir probes range from 5 to 300 eV.

Data have been taken from both discharges with an analog-to-digital data handling system which allows us to analyze the digital time series

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generated by electrostatic potential fluctuations detected by capacitive probes at two azimuthal or axial positions in the plasma. Auto- and cross-power spectra, the phase coherence spectrum, and dispersion relations have been observed for both plasmas. Rotating spokes, driven by E/B drift, and propagating waves have been observed and their dispersion relations obtained. These electrostatic potential fluctuations have been compared and correlated with microwave scattering results from the classical Penning discharge plasma.

RF emissions over the frequency range from 100 to 1400 MHz have been measured in the far radiation field with a spectrum analyzer connected to a specially calibrated broadband conical spiral antenna. The plasmas emit radiation with numerous harmonics of a fundamental frequency over a broad frequency range up to at least 2 GHz [4,5,6]. We have also used our antenna to make local power flux and net radiated power measurements. Axial ion energy distribution functions were measured with a retarding potential energy analyzer in both discharges, and varied from monoenergetic to Maxwellian with characteristic energies from below 100 eV to several keV. High levels of electrostatic turbulence resulted in more nearly Maxwellianized energy distributions. The modified Penning discharge seemed to produce more nearly Maxwellianized distribution functions than the classical Penning discharge, with its flat axial magnetic field profile. In both discharges, profiles of plasma potential and electron number density and kinetic temperature were taken along the axis of symmetry with a Langmuir probe under a variety of operating conditions.

2. The Modified Penning Discharge

With helium gas at pressures above 2×10^{-4} Torr, the axial profile of electrostatic potential was quite flat, with axial electric fields of only a few volts per centimeter at most. Below 10^{-4} Torr, however, electric fields up to 100 volts/cm were observed. On Fig. 1a is an example of a monotone decreasing axial potential profile for a gas pressure of 4×10^{-5} Torr of helium, B_{max} = 0.15 Tesla, anode voltage V_a = 4700 volts, a maximum number density on the midplane of $1.2 \times 10^{8}/cm^{3}$, and a characteristic T_e = 60 eV. On Fig. 1b is an interesting example not only of strong axial electric fields, but of an axial electrostatic potential well for ions, about 600-800 eV deep. The helium gas pressure and magnetic field were approximately twice that of Fig. 1a; $T_e \approx 300$ eV, and other parameters were approximately the

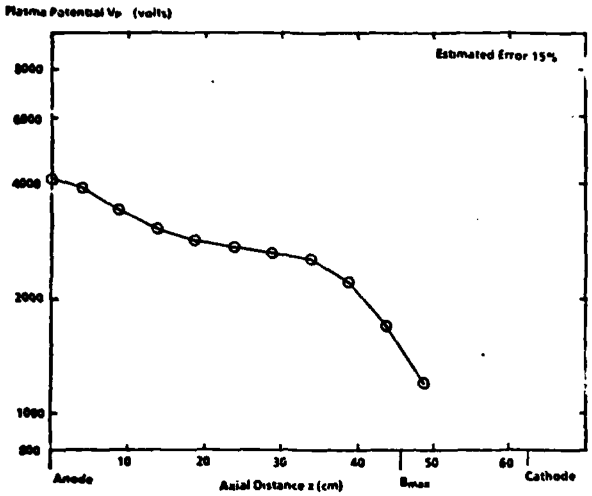

Figure 1A

Axial Profile of Plasma Potential $P_0 = 4 \times 10^{[illegible]}$ torr , He gas

B_{max} = 1.5 kilogauss , V_{anode} = 4700 volts

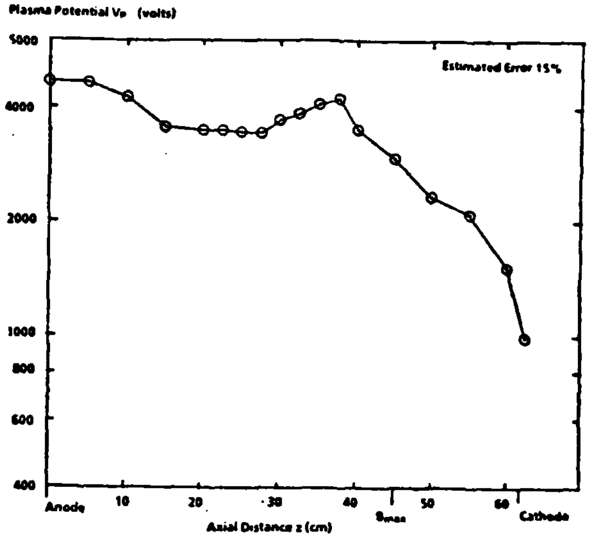

Figure 1B

Axial Profile of Plasma Potential $P_0 = 8.4 \times 10^{[illegible]}$ torr , He gas

B_{max} = 3.0 kilogauss , V_{anode} = [illegible] volts

same. Both plasmas were highly turbulent, and the energy of ions escaping to the cathodes (measured with a retarding potential energy analyzer) were on the order of kilovolts. The high axial electric fields observed imply a very high anomalous resistivity for the plasma. This plasma emits multiple harmonics of a fundamental frequency which appears to be the geometric mean emission frequency associated with the interpenetrating beam plasma instability [3]. The envelope of these harmonic peaks has a maximum which is consistent with the electron plasma frequency of this discharge.

3. The Classical Penning Discharge

The classical Penning discharge also emits broadband RF radiation and under certain circumstances, the spectrum is white-noise like from 0.6 MHz to above 1.0 GHz [4]. Significant radiation has been observed above 2.0 GHz. Harmonics of the geometric mean emission frequency are observed, with a maximum envelope amplitude near the electron plasma frequency.

Measurements from a microwave scattering apparatus consisting of a 27 GHz Gunn diode in a homodyne mixer configuration were taken. Approximately 100 milliwatts of microwave power was incident on the plasma in the ordinary mode. The scattered power is observed in a plane normal to the plasma axis for scattering angles from 20° to 160°. When the scattered signal from the crystal detector is fed into a spectrum analyzer, electron number density fluctuations from 10 to 40 kHz are observed. These appear to obey a linear dispersion relation. On Figure 2a is shown an example of the spectrum of microwave scattering signals for argon gas at a

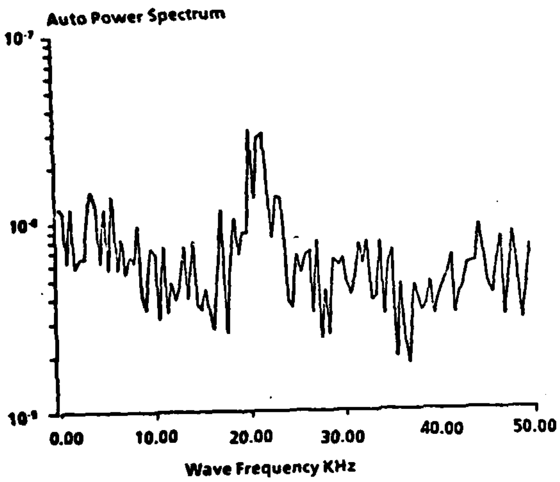

Figure 2A

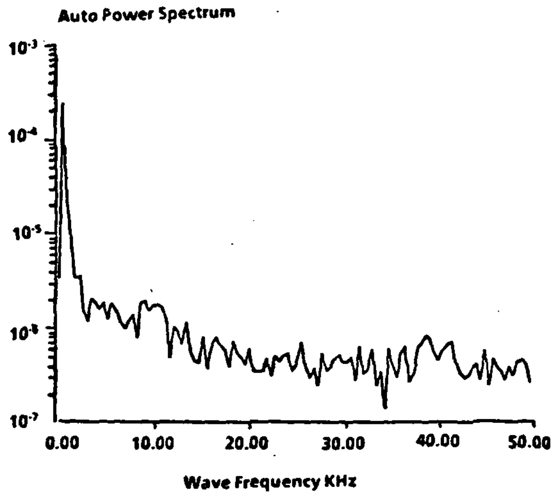

Figure 2B

pressure of 3.5 x 10^{-4} Torr, at an anode voltage of V_a = 1.8 kV, and a magnetic field of B = 0.25 Tesla. On Figure 2b is an example of the auto power spectrum taken under the same operating conditions from a capacitive probe about 3 cm outside the plasma boundary. This shows no peak in the range from 10 kHz to 50 kHz.

Acknowledgements

The classical Penning discharge investigations were supported by AFOSR contract #81-0093, and the modified Penning discharge research by ONR contract #N00014-80-C-0063.

References

1. Penning, F. M.: and Nienhuis, K.: Philips Technical Review 11, No. 4 (1949), pp. 116-122.
2. Roth, J. R.: RSI 37, No. 8. 8, Aug. 1966, pp. 1100-1101.
3. Alexeff, I.; Roth, J. R.; Birdwell, J. D.; and Mallavarpu, R.: Physics of Fluids, Vol. 24, No. 7, 1348-1357 (1981).
4. Roth, J. R.; Hayman, P. W.; and Pastel, R. L.: Proceedings of the International Conference on Plasma Physics, Goteborg, Sweden, June 9-15, (1982) p. 250.
5. Spence, P. D.; and Roth, J. R.: "Axial and Radial Profiles of Plasma Parameters in an RF-Emitting Modified Penning Discharge", APS Bulletin, Vol. 28, No. 8, p. 1256-1265, (1983).
6. Pastel, R. L.; and Roth, J. R.: "Axial Electric Fields and Electron Number Density Profiles in a Classical Penning Discharge", APS Bulletin, Vol. 28, No. 8, pp. 1256-57 (1983).

Paper 27A: P1

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ABSTRACT

We have operated steady-state classical and modified Penning discharges in uniform and magnetic mirror geometries respectively [1]. The classical geometry consists of a uniform magnetic field up to 0.40 Tesla, and the modified Penning discharge of a 5.7:1 magnetic mirror geometry with a maximum magnetic field on the axis up to 0.40 Tesla. The electrons are trapped in an electrostatic potential well, and in both cases form a plasma about 10 cm in diameter in the midplane, and about 70 cm long. The electron population forms two interpenetrating beams in the background plasma which give rise to the interpenetrating beam and other plasma instabilities [2]. These plasmas support high levels of electrostatic turbulence, axial electric fields up to several hundred volts per centimeter, and emit broadband electromagnetic radiation over the frequency range from below 1 MHz to more than 2 GHz [3].

We have applied a 27 GHz microwave scattering apparatus to the classical Penning discharge. Electron number density fluctuations are observed in the range from 10 to 40 kHz. Data have been taken from both discharges for various plasma operating conditions with an analog-to-digital data handling system which allows us to analyze the digital time series generated by electrostatic potential fluctuations detected by capacitive probes at two azimuthal or axial positions in the plasma. Auto power spectra, cross power spectra, the phase coherence spectrum and dispersion relations have been observed for both plasmas. Rotating spokes and other propagating waves have been observed, and their dispersion relations obtained. These fluctuations have been compared with the microwave scattering results from the classical Penning discharge.

RF emissions over the frequency range from 50 to 1400 MHz have been observed in the far radiation field with a specially developed broadband conical spiral antenna. The plasma emits radiation with numerous harmonics of a fundamental frequency over a broad frequency range up to at least 2 GHz. We have also used our antenna to make local power flux and net radiated RF power measurements. The RF emission spectra are compared with the results of the propagating wave and turbulence data from the capacitive probes on both Penning discharges, and also with the microwave scattering data from the classical Penning discharge.

*Supported by ONR contract N-00014-80-C-0063 and AFOSR contract 81-0093.

[1] J. R. Roth, RSI, 37, (1966) 1100-1101.
[2] I. Alexeff, J. R. Roth, J. D. Birdwell, and R. Mallavarpu, Phys. Fluids, 24, (1981), 1348-57.
[3] J. R. Roth, P. W. Hayman, and R. L. Pastel, Paper 11P-II-02, Proc. 1982 International Conf. on Plasma Physics, Goteborg, Sweden, p. 250.

THE MODIFIED PENNING DISCHARGE

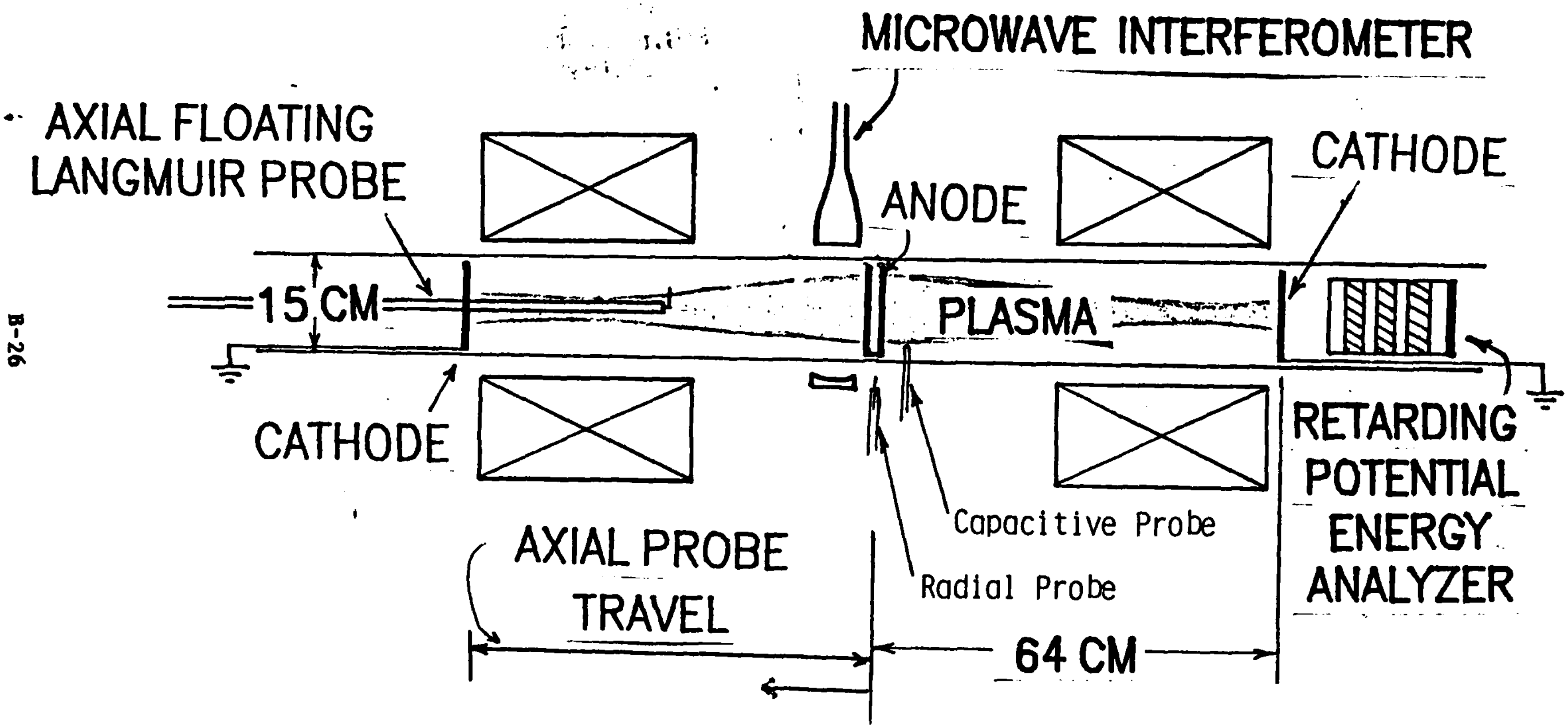
CONSISTS OF A STEADY—STATE PENNING DISCHARGE IN A 5:1 MAGNETIC MIRROR FIELD.

HAS STRONG (ABOVE 100 VOLT/CM) ELECTRIC FIELDS PARALLEL TO THE MAGNETIC FIELD.

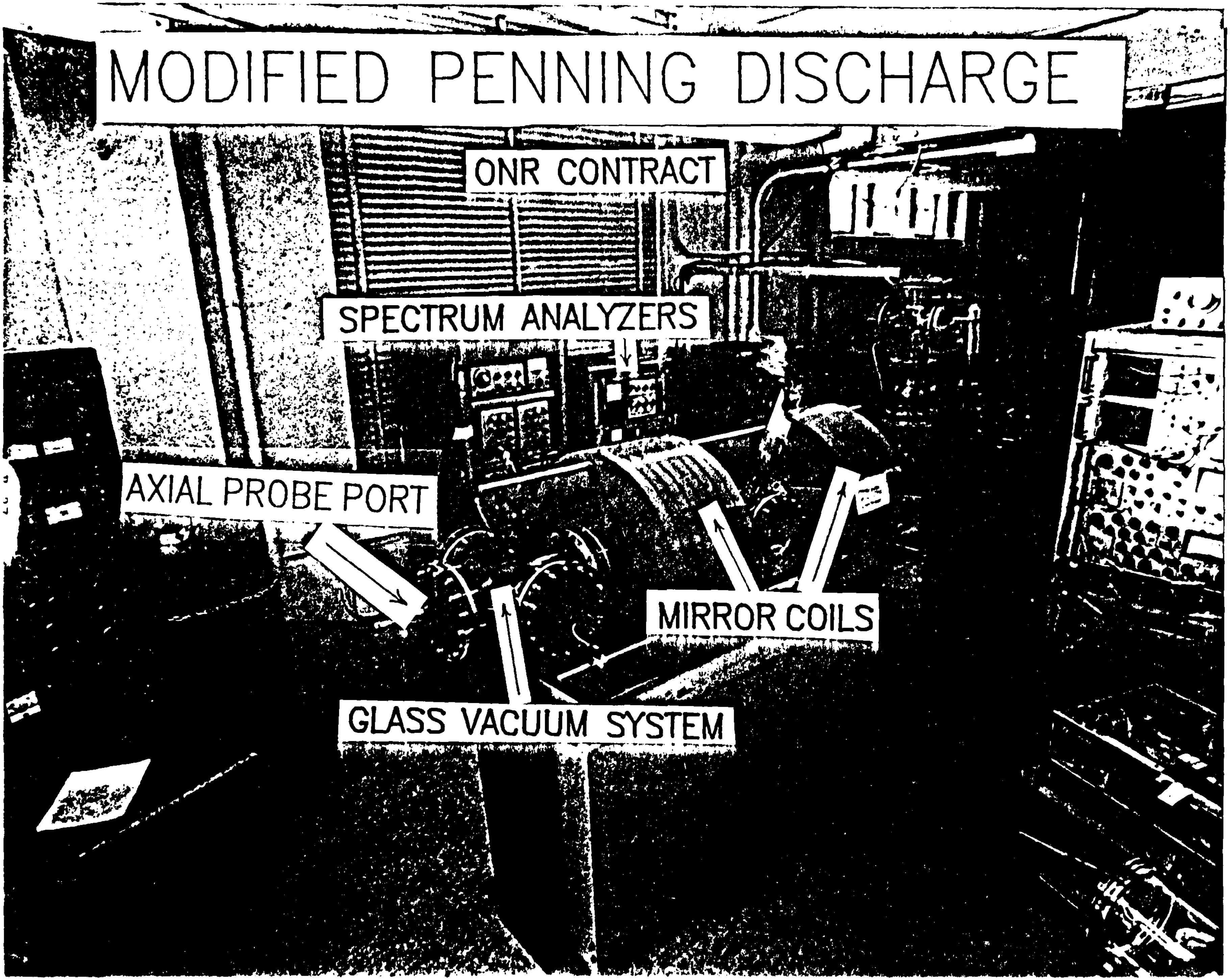
PRODUCES IONS WITH KILOVOLT LONGITUDINAL ENERGIES AS MEASURED WITH A RETARDING POTENTIAL ENERGY ANALYZER.

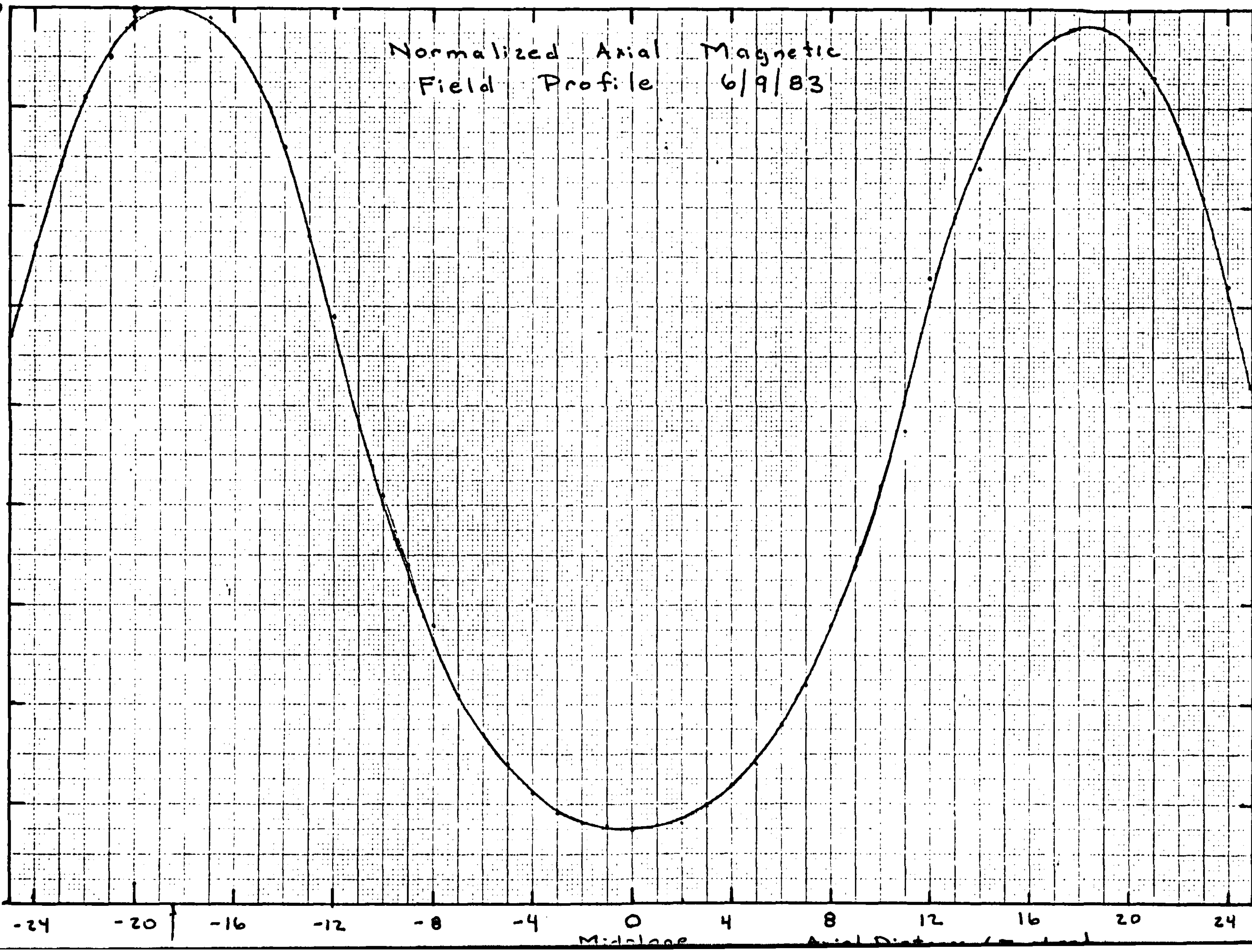
OPERATES IN TWO MODES, SEPARATED BY A DISCONTINUITY IN THE CURRENT—VOLTAGE PLANE.

IN ARGON GAS, EXHIBITS A FLAT SPECTRUM OF RF EMISSION FROM 0.5 MHz TO 1.0 GHz



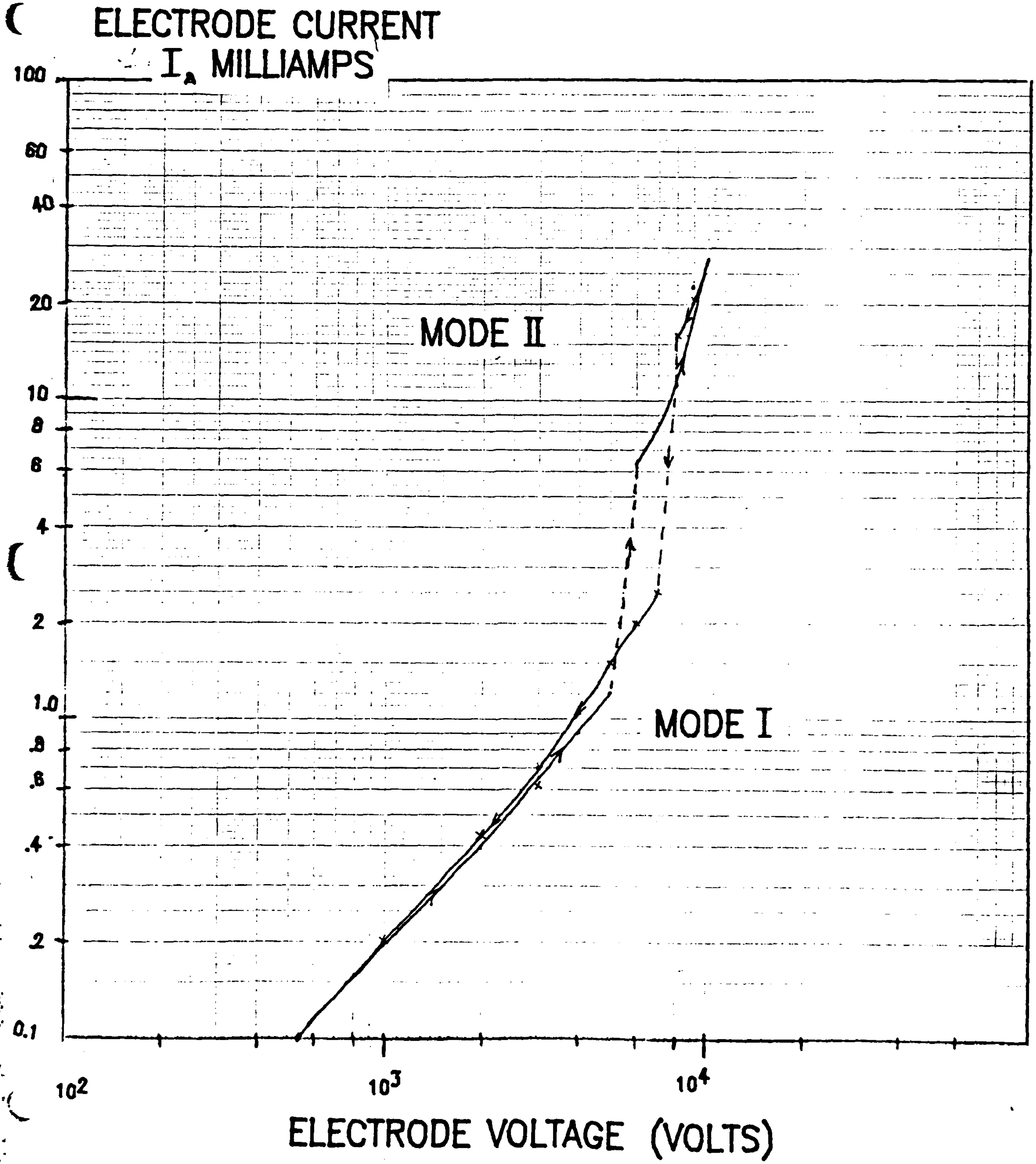
MODIFIED PENNING DISCHARGE

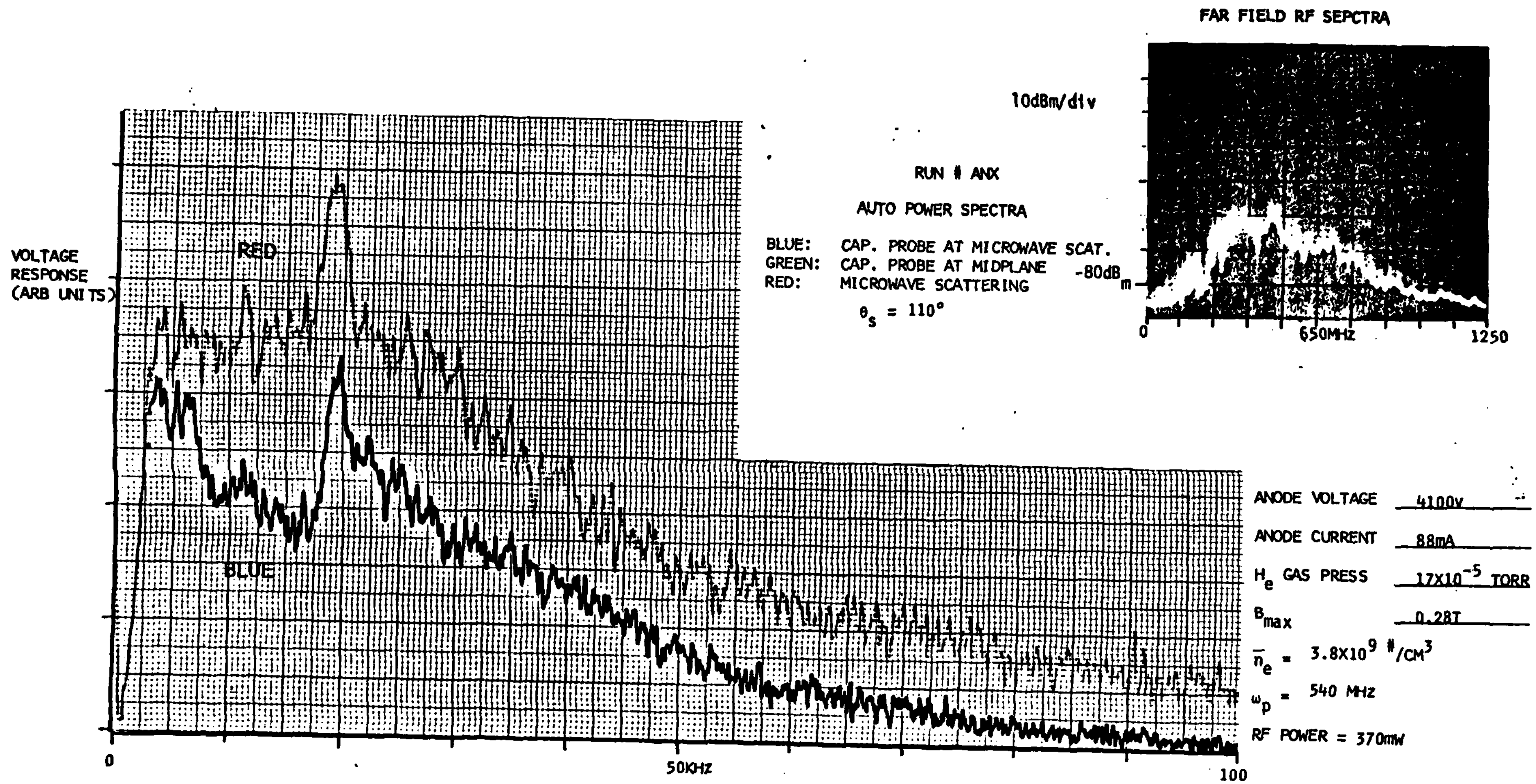

MODIFIED PENNING DISCHARGE
ONR CONTRACT
SPECTRUM ANALYZERS
AXIAL PROBE PORT
MIRROR COILS
GLASS VACUUM SYSTEM



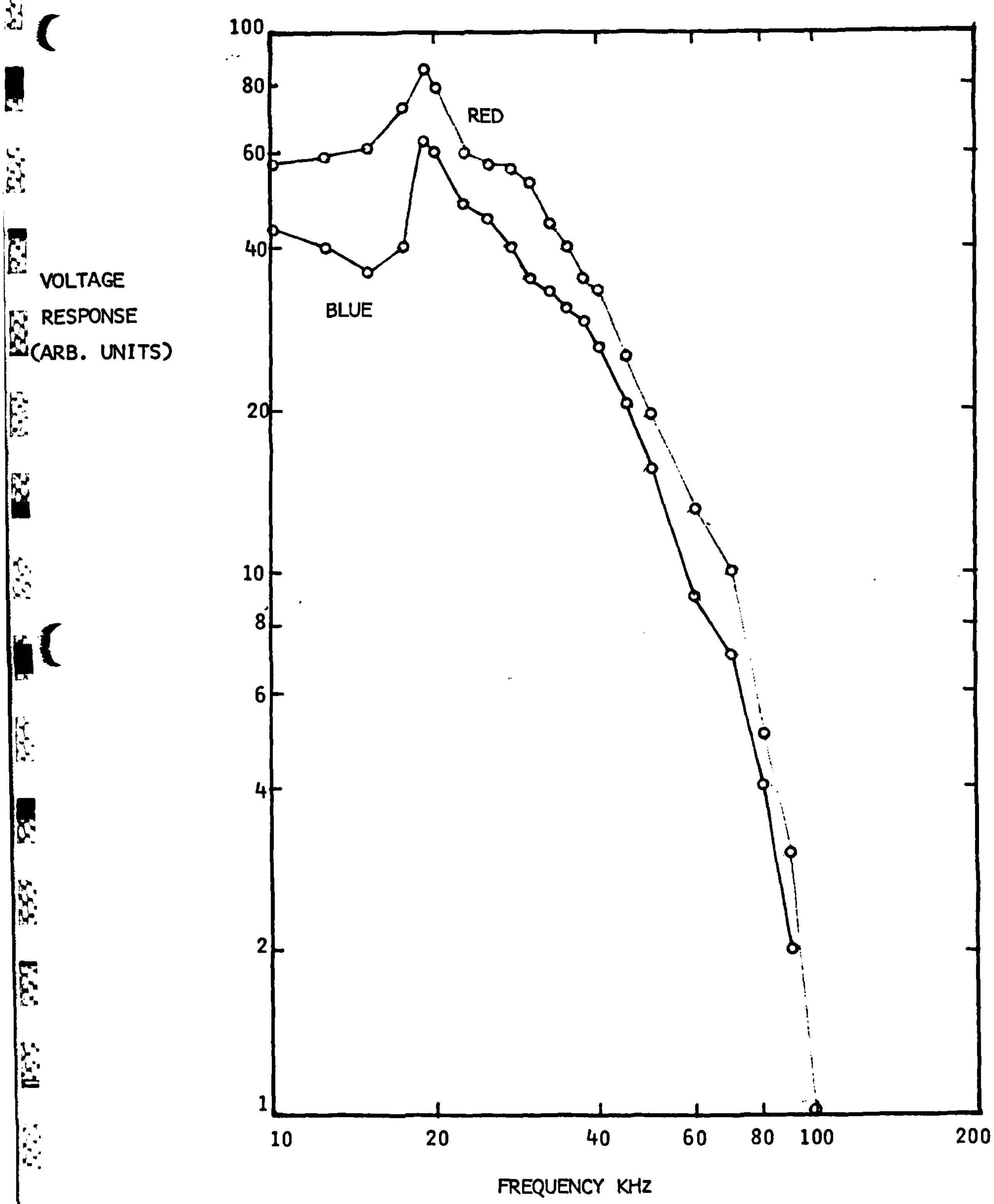
0 Millimeters to the Centimeter

MODIFIED PENNING DISCHARGE

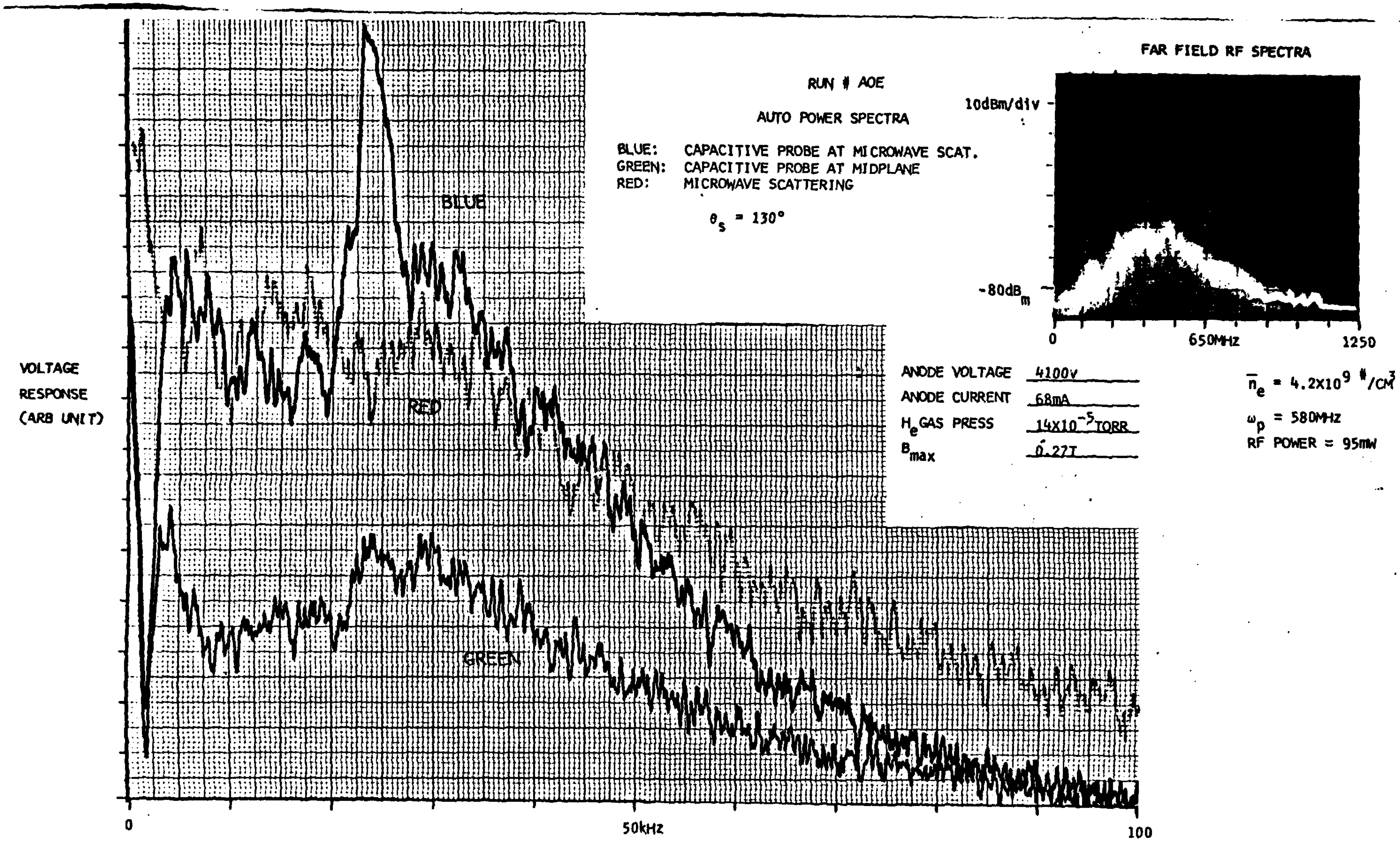



FAR FIELD RF SEPCTRA
10dBm/div
-80dBm
0
650MHz
1250
RUN # ANX
AUTO POWER SPECTRA
BLUE: CAP. PROBE AT MICROWAVE SCAT.
GREEN: CAP. PROBE AT MIDPLANE
RED: MICROWAVE SCATTERING
$\theta_s = 110°$
VOLTAGE RESPONSE (ARB UNITS)
RED
BLUE
0
50KHz
100
ANODE VOLTAGE 4100V
ANODE CURRENT 88mA
H_e GAS PRESS $17X10^{-5}$ TORR
B_{max} 0.28T
$\bar{n}_e = 3.8X10^9$ #/CM^3
ω_p = 540 MHz
RF POWER = 370mW

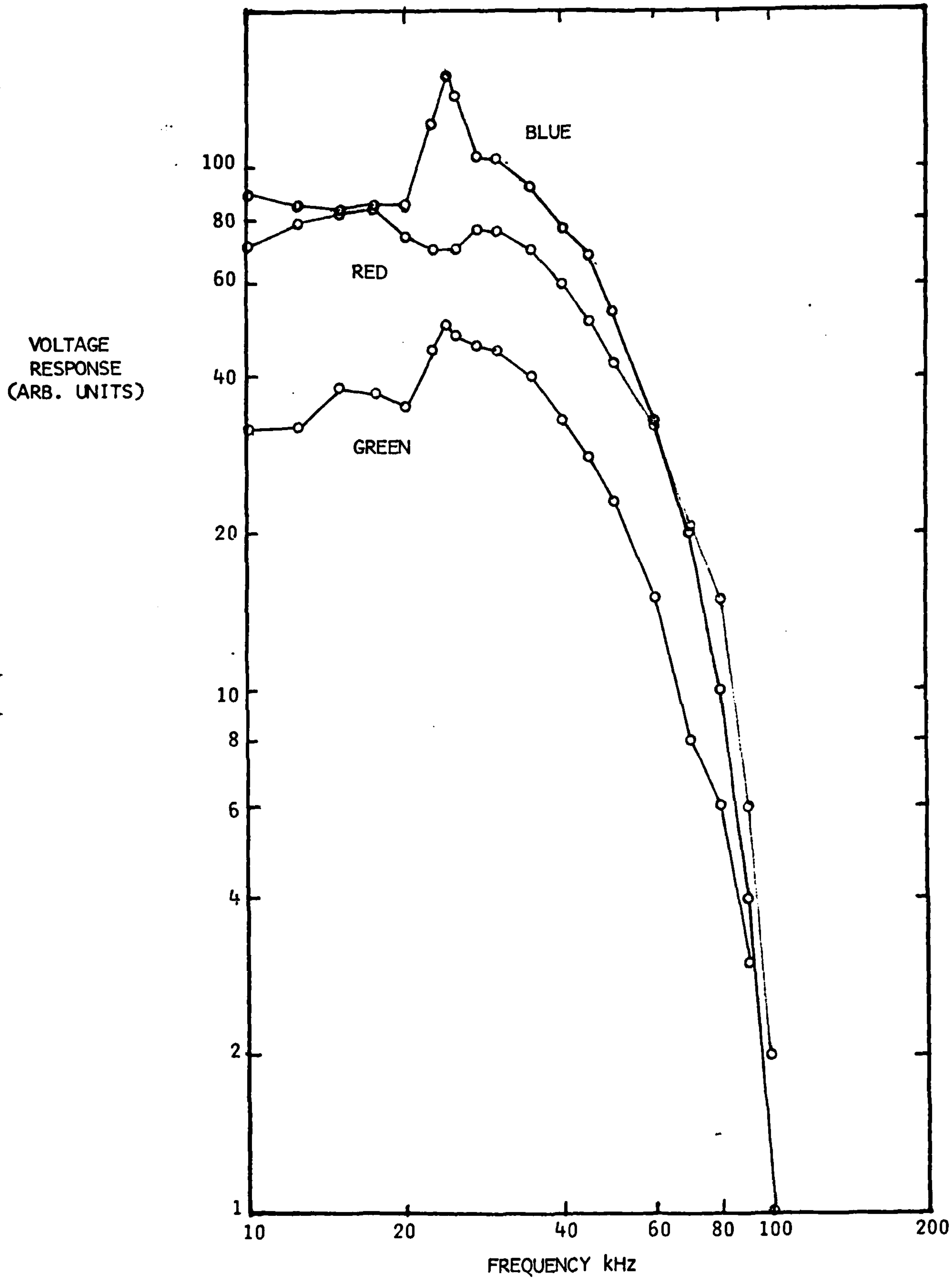
RUN # ANX



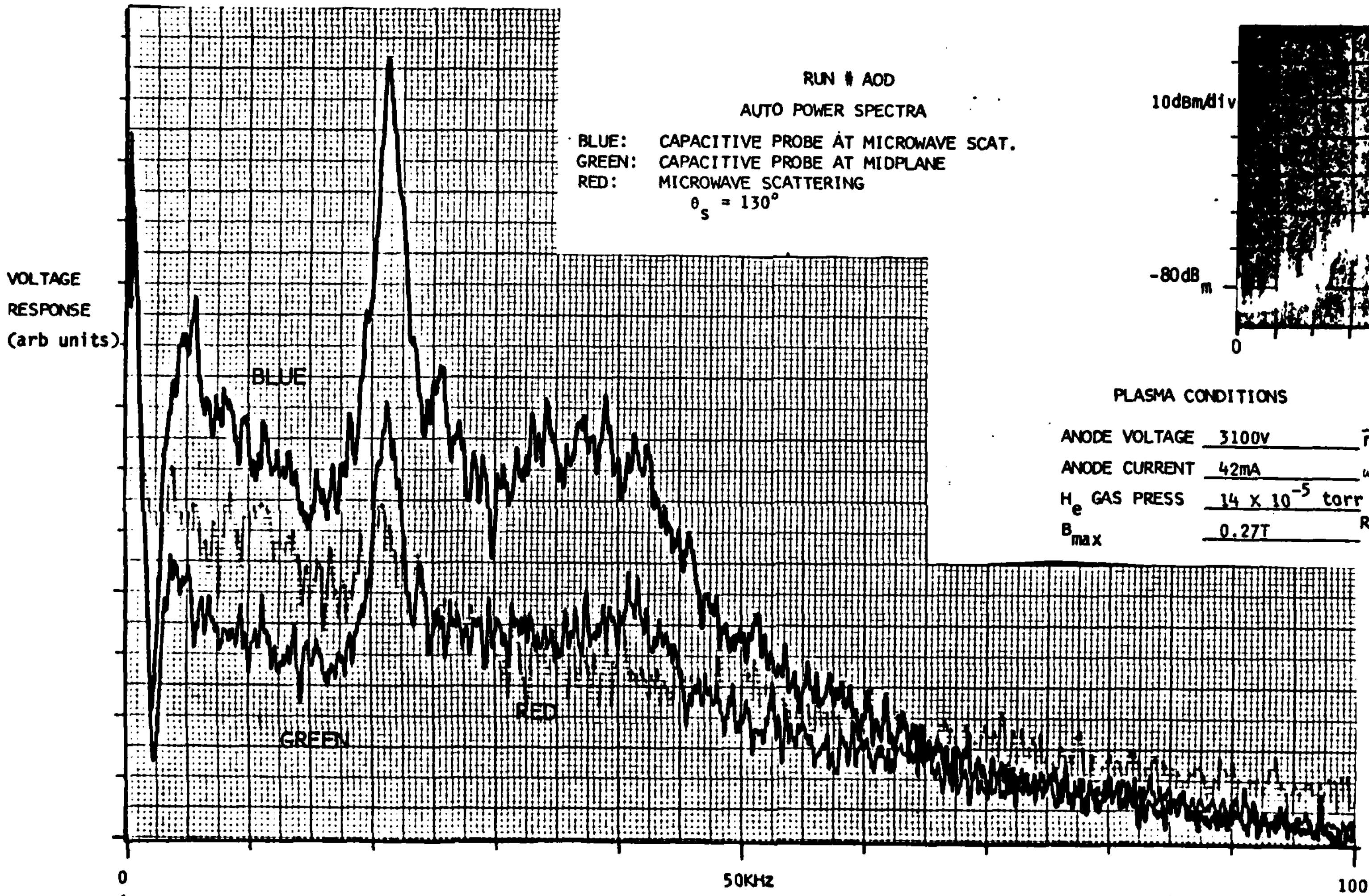
RED: MICROWAVE SCATTERING
BLUE: CAPACITIVE PROBE AT MICROWAVE


RUN # AOE
AUTO POWER SPECTRA
BLUE: CAPACITIVE PROBE AT MICROWAVE SCAT.
GREEN: CAPACITIVE PROBE AT MIDPLANE
RED: MICROWAVE SCATTERING
$\theta_s = 130°$
FAR FIELD RF SPECTRA
10dBm/div
-80dB$_m$
0
650MHz
1250
VOLTAGE RESPONSE (ARB UNIT)
BLUE
RED
GREEN
ANODE VOLTAGE 4100v
ANODE CURRENT 68mA
H_e GAS PRESS $14X10^{-5}$ TORR
B_{max} 0.27T
$\bar{n}_e = 4.2X10^9$ #/CM^3
ω_p = 580MHz
RF POWER = 95mW
0
50kHz
100

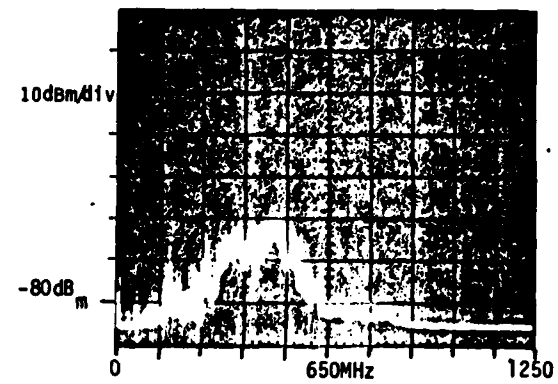
RUN # AOE AUTO POWER SPECTRA



GREEN: CAPACITIVE PROBE AT MIDPLANE
BLUE: CAPACITIVE PROBE AT MICROWAVE SCAT.
RED: MICROWAVE SCATTERING



FAR FIELD RF SPECTRA



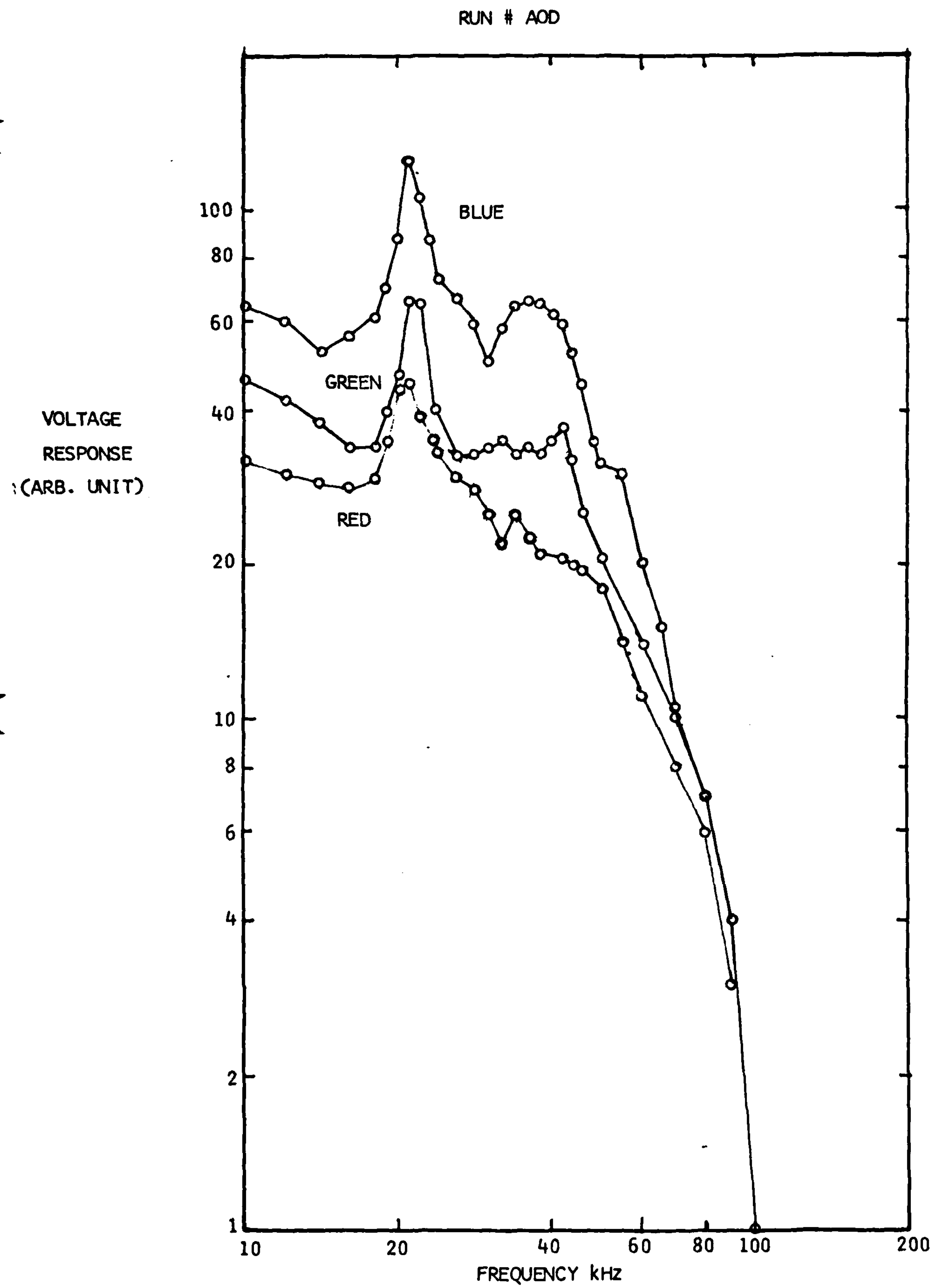
PLASMA CONDITIONS

ANODE VOLTAGE 3100V $\bar{n}_e = 4.2 \times 10^9$ #/CM^3

ANODE CURRENT 42mA ω_p = 580MHz

H_e GAS PRESS 14×10^{-5} torr

B_{max} 0.27T RF POWER 70mW



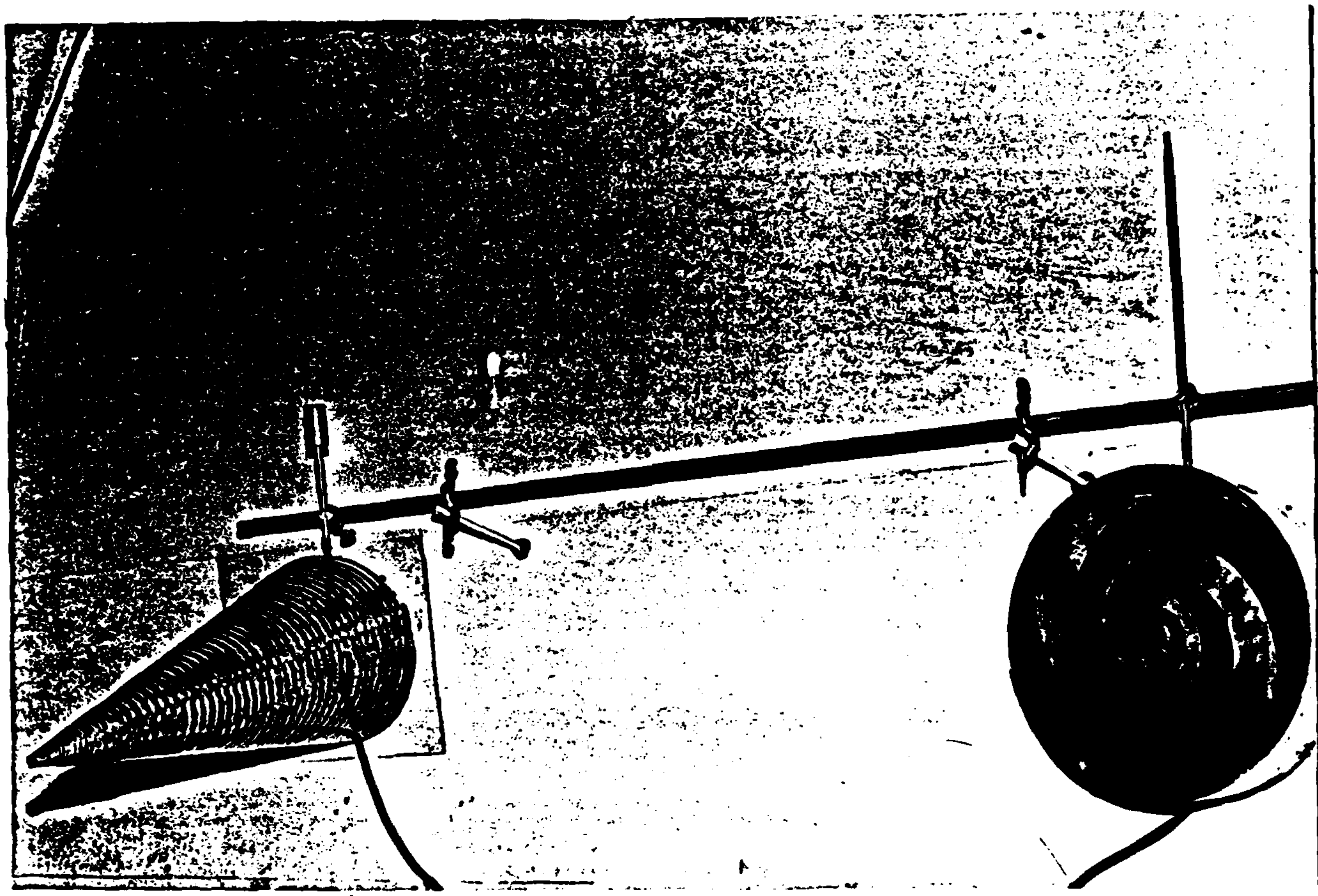
GREEN: CAPACITIVE PROBE AT MIDPLANE
BLUE: CAPACITIVE PROBE AT MICROWAVE SCAT.
RED: MICROWAVE SCATTERING

Power Measurements:

Absolute power measurements of Far field RF power flux were made from the modified Penning Discharge, using a calibrated conical spiral antenna and a calibrated planar log spiral antenna. These antennae have approximately constant apertures over the frequency range of interest. The conical spiral was located 2.2 meters to 2.9 meters uder a variety of plasma conditions. The planar spiral was located from 2.5 meters to 3.1 meters during power measurements. The net power captured by the antenna from 100 MHz to 1000 MHz was measured using an HP 432A power meter with a 478A thermistor mount. A 1000 MHz low pass filter was inserted, and for the conditions studied less than 10% of the detected power was above 1GHz. Due to polarization a 3dBm correction was added to the detected power, as well as a l dBm correction for cable lesses.

The plasma was taken to radiate spherically and consequently the net RF power was taken to be the local power flux at the antenna integrated over 4π steradian. This RF power as a function of input power is shown in graph 1. The efficiency of the plasma as a microwave source is also plotted in graph 2.

FIGURE 1



CONICAL SPIRAL

PLANER LOG SPIRAL

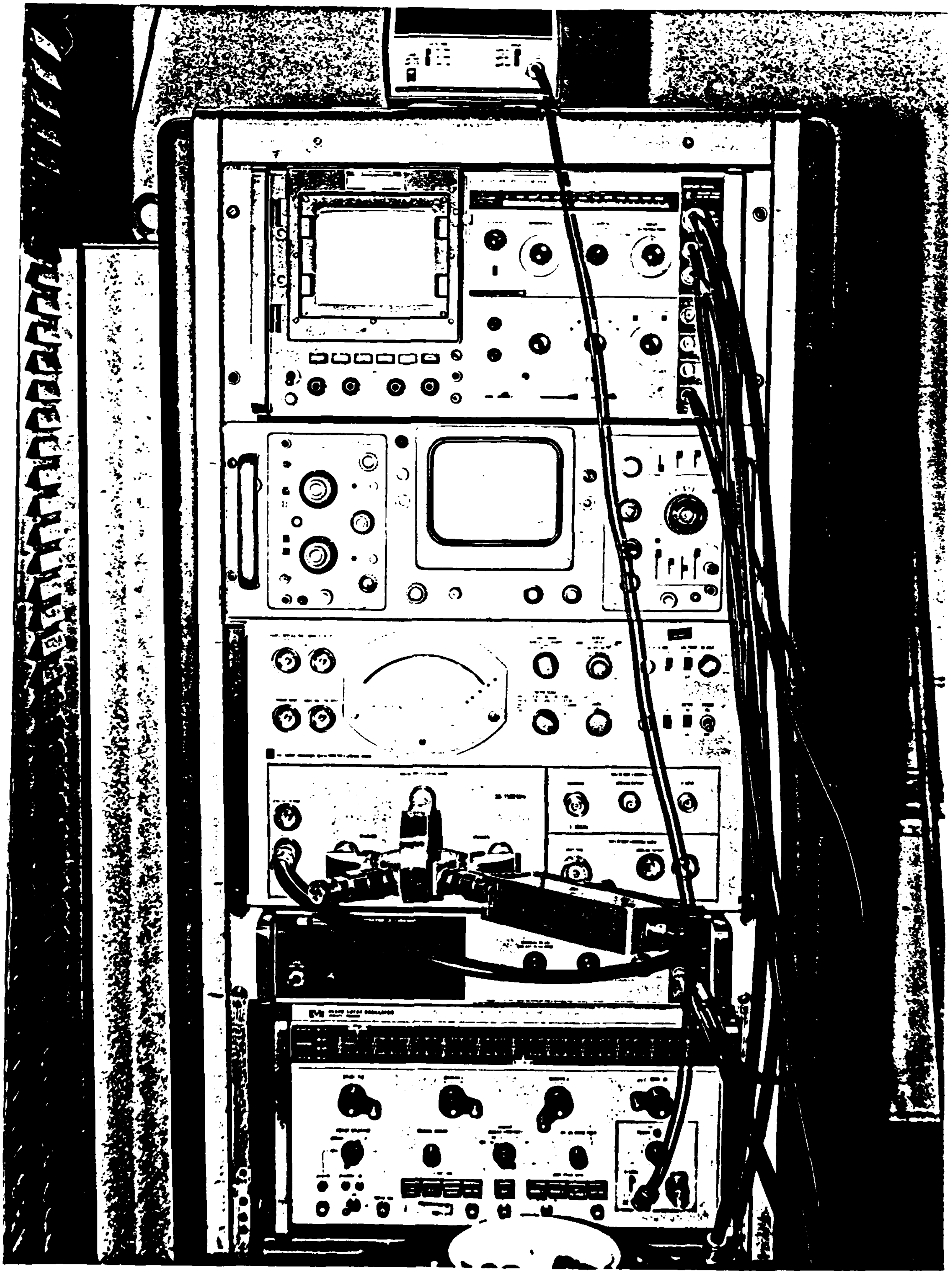


FIGURE 4
RF SPECTRUM - CONICAL SPIRAL

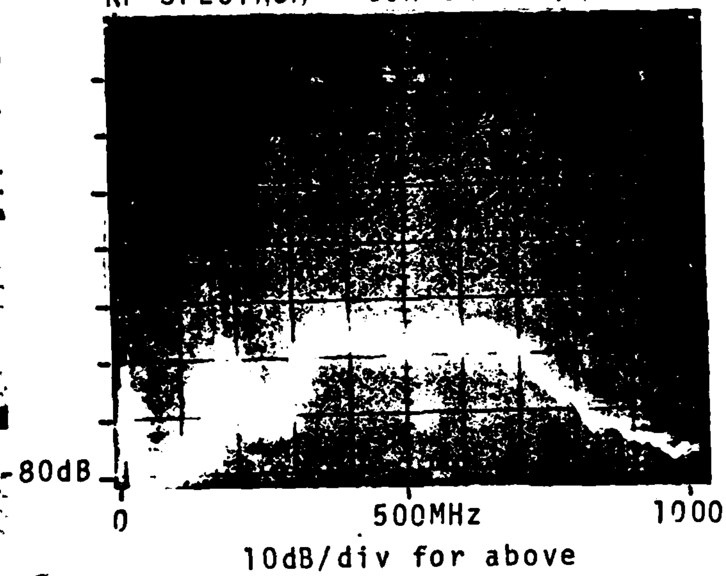


FIGURE 6
RF SPECTRUM - CONICAL SPIRAL

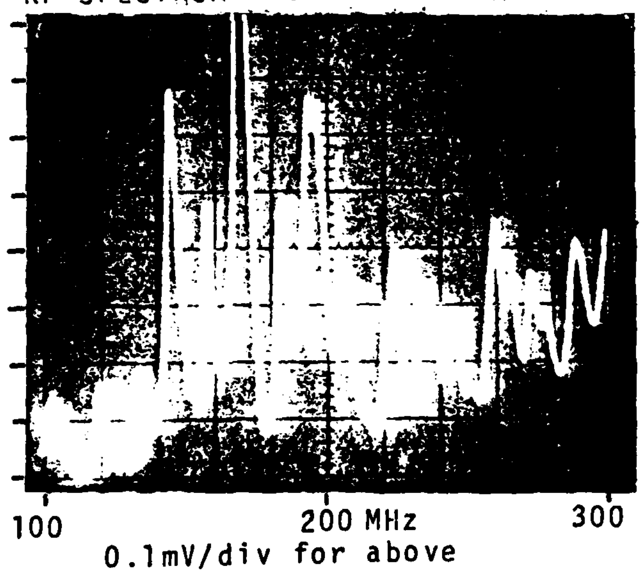


FIGURE 5
RF SPECTRUM - PLANAR SPIRAL

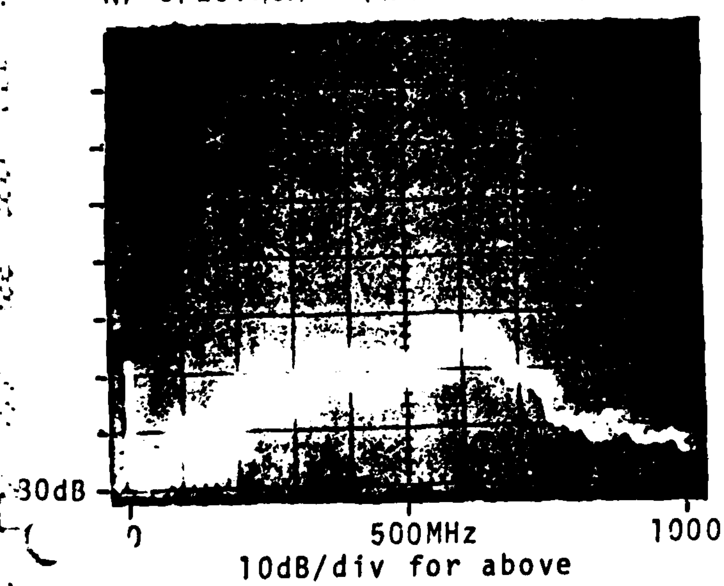
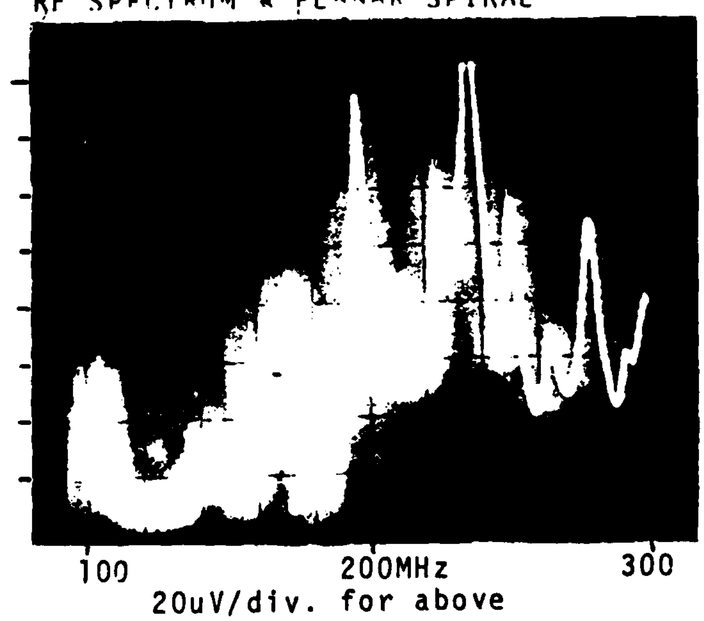
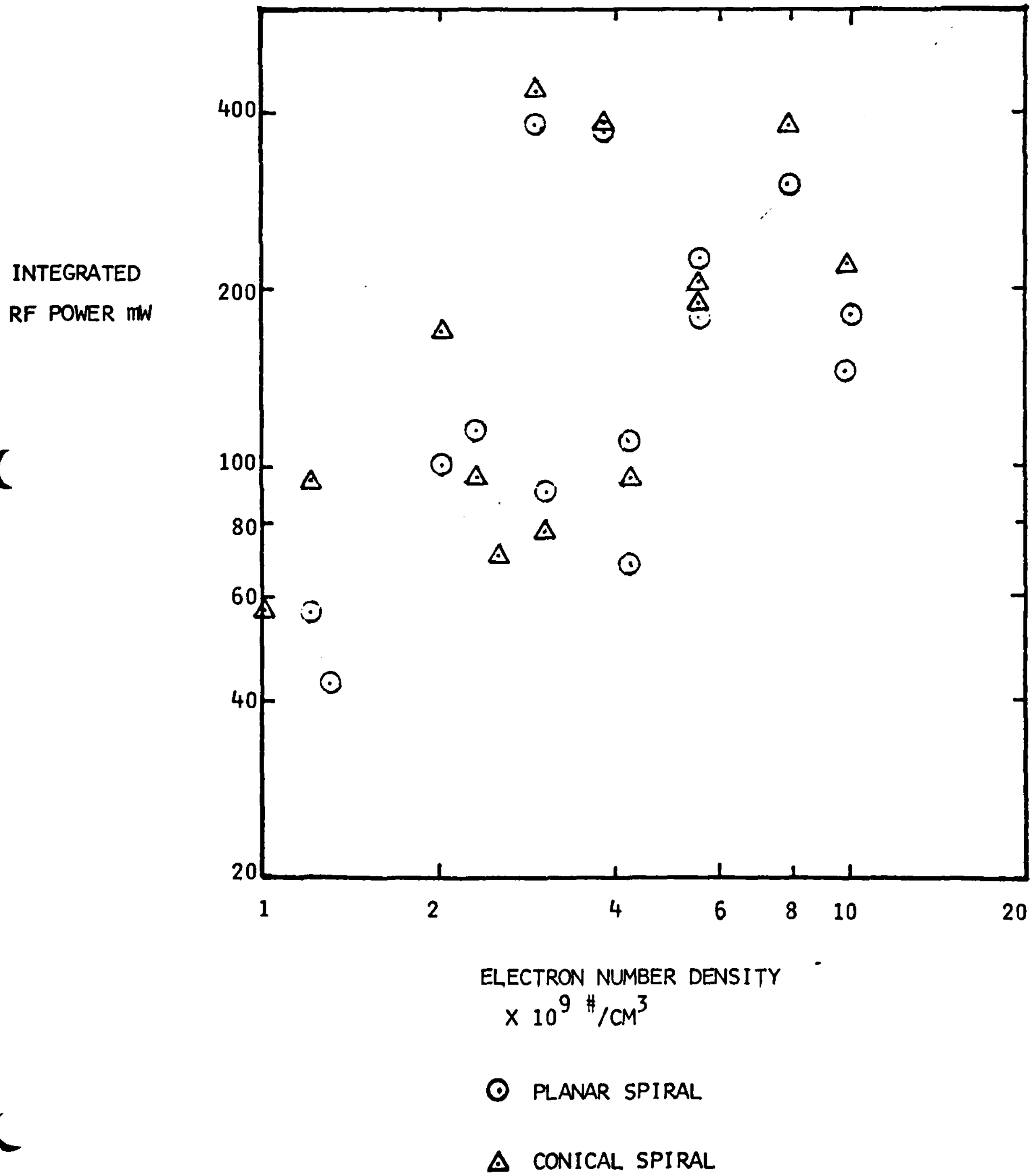


FIGURE 7
RF SPECTRUM - PLANAR SPIRAL



GRAPH 4

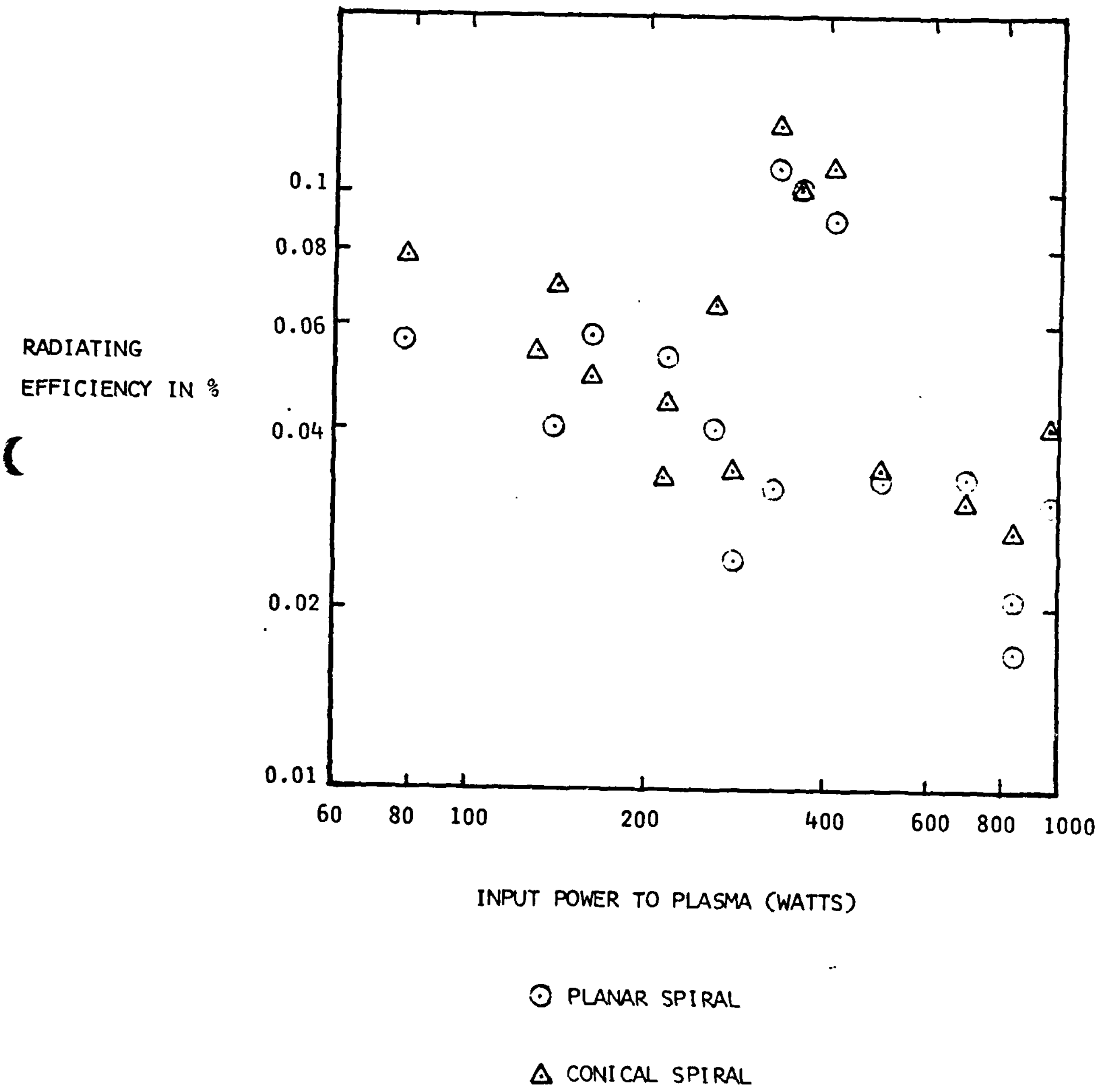
INTEGRATED RF POWER VS. ELECTRON NUMBER DENSITY



$$\text{RADIATING EFFICIENCY} = \frac{\text{INTEGRATED RF POWER}}{\text{INPUT PLASMA POWER}}$$

VS

INPUT PLASMA POWER



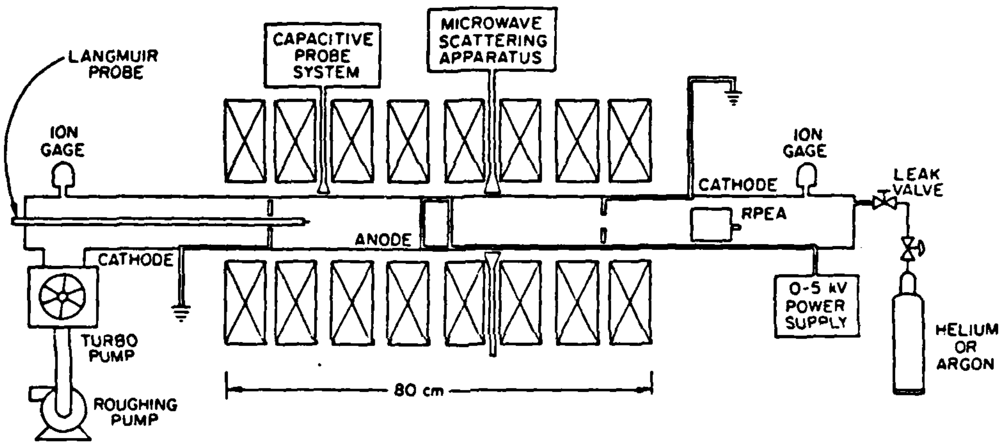
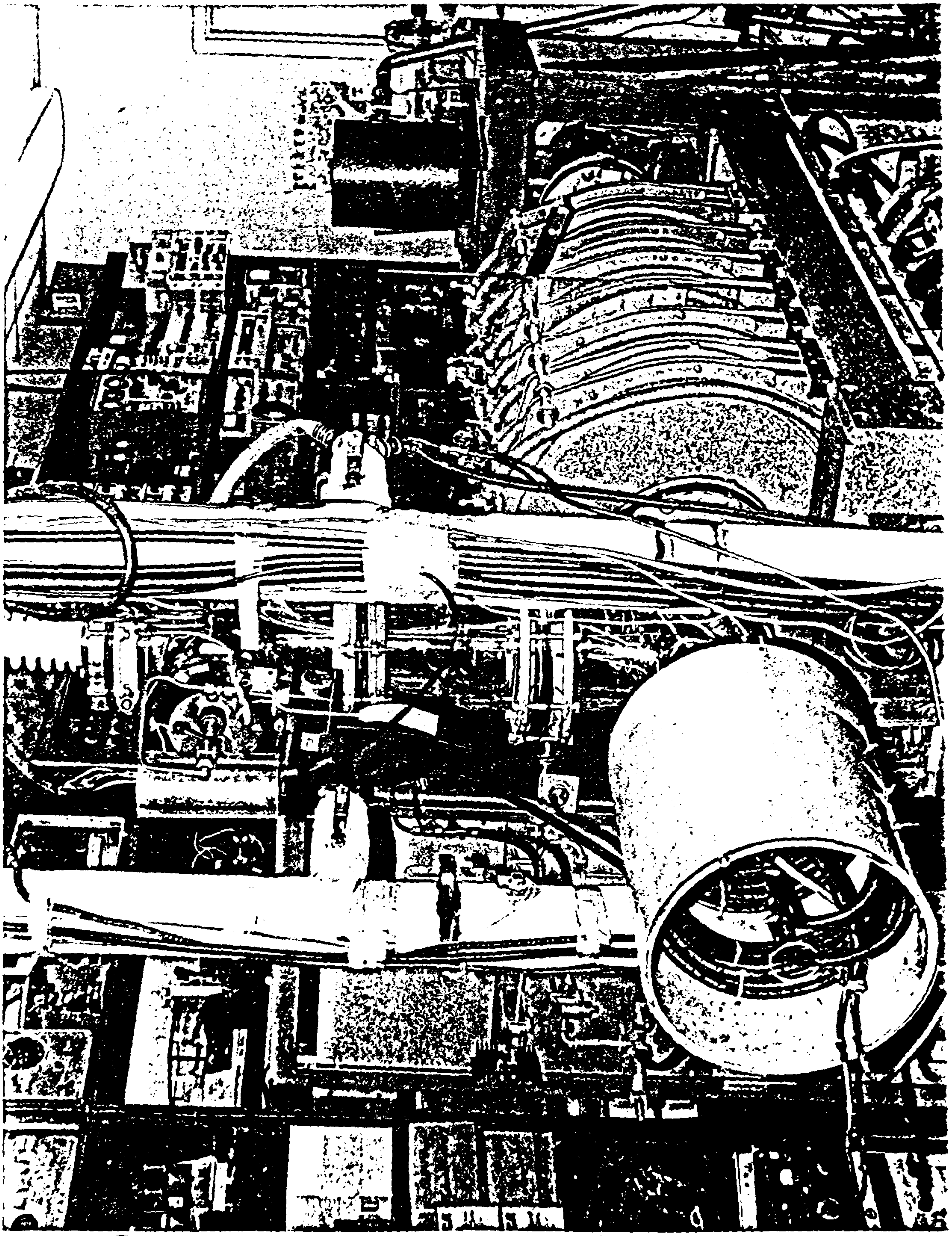


Figure 3.1. Penning discharge schematic.



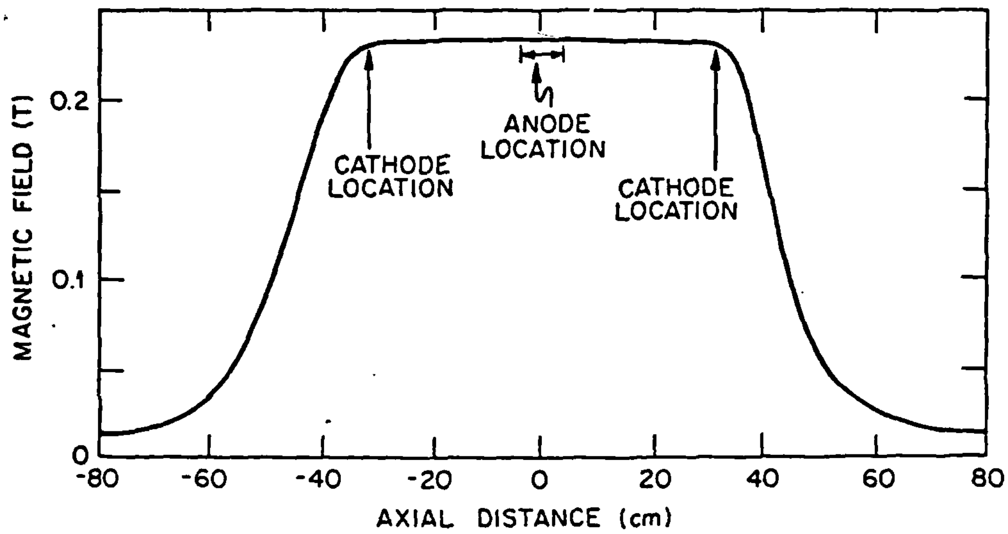


Figure 3.3. Axial magnetic field of UT classical Penning discharge.

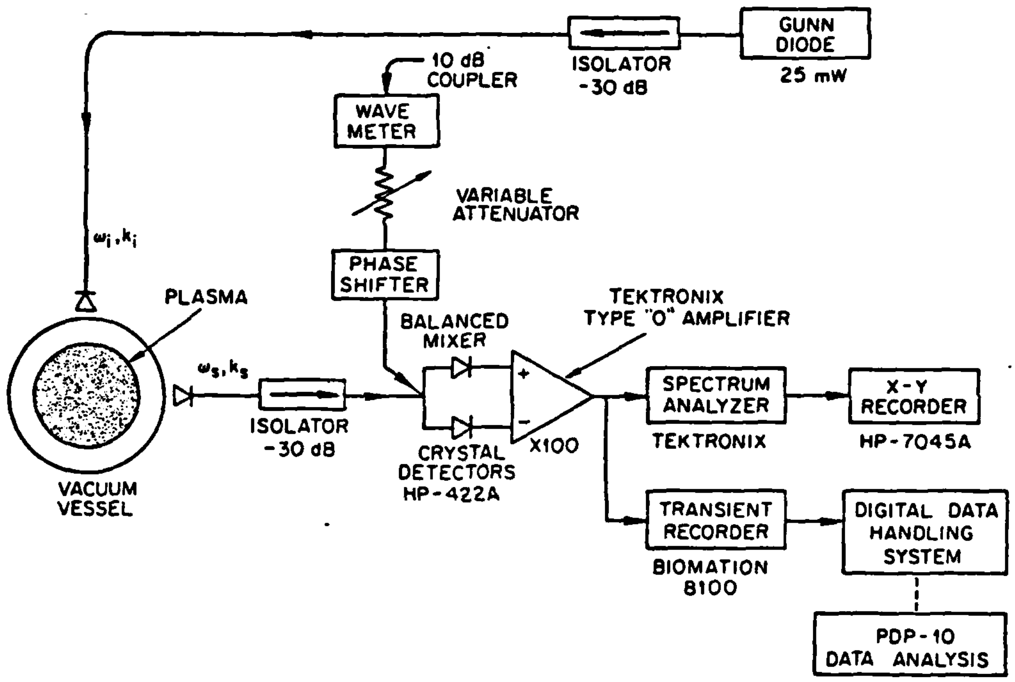
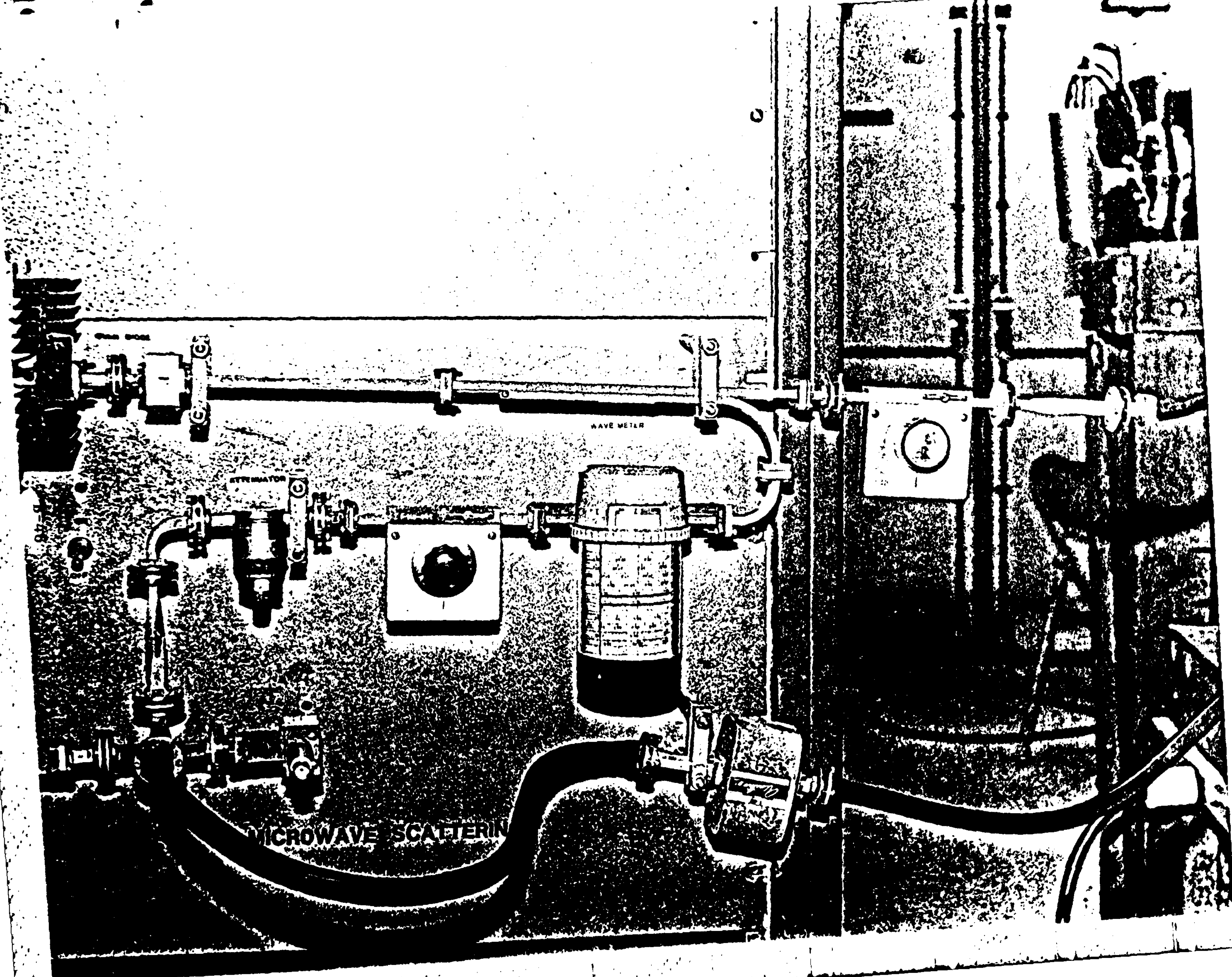


Figure 3.6. Microwave scattering experimental setup.


WAVE METER
MICROWAVE SCATTERIN

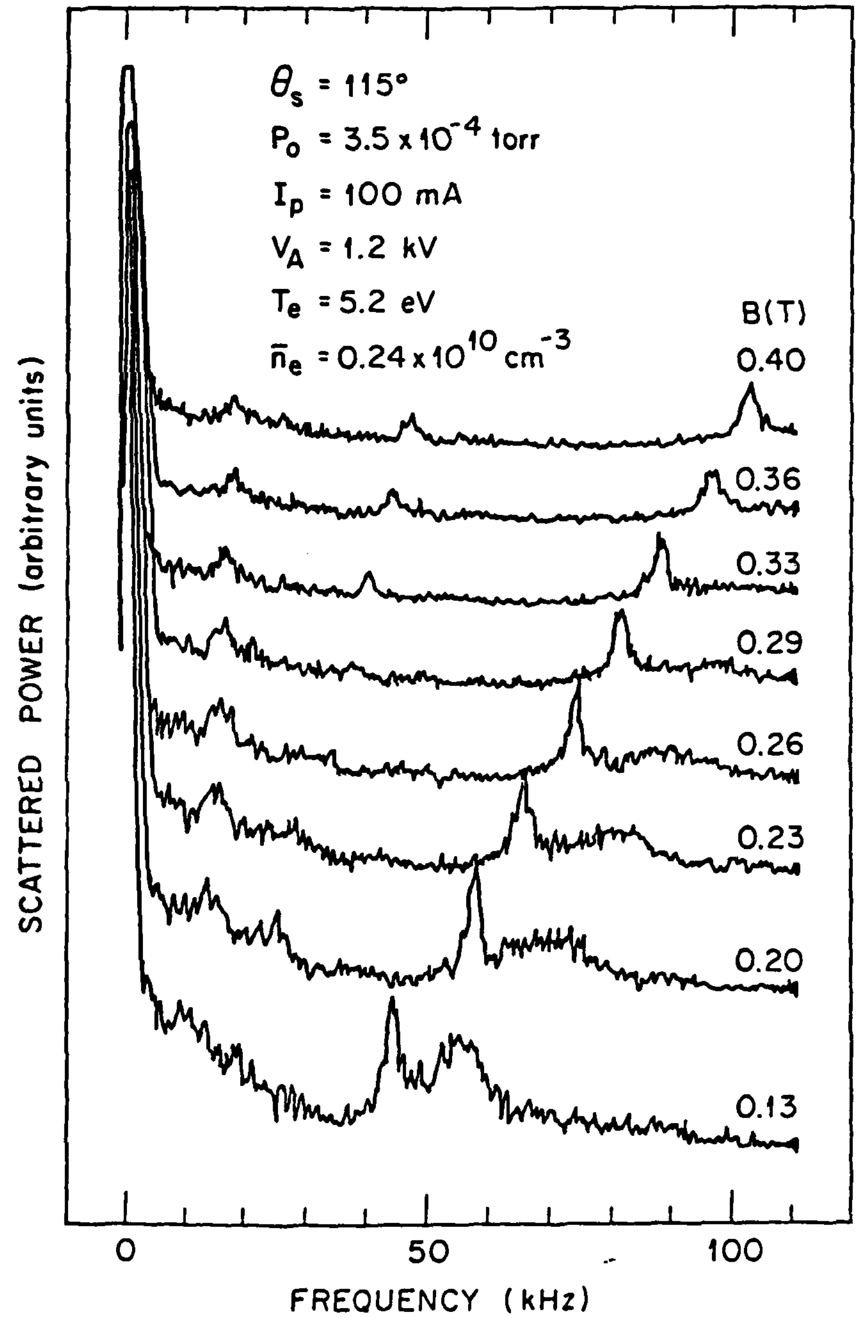


Figure 4.4. Comparison of turbulence frequency spectra on magnetic field strength.

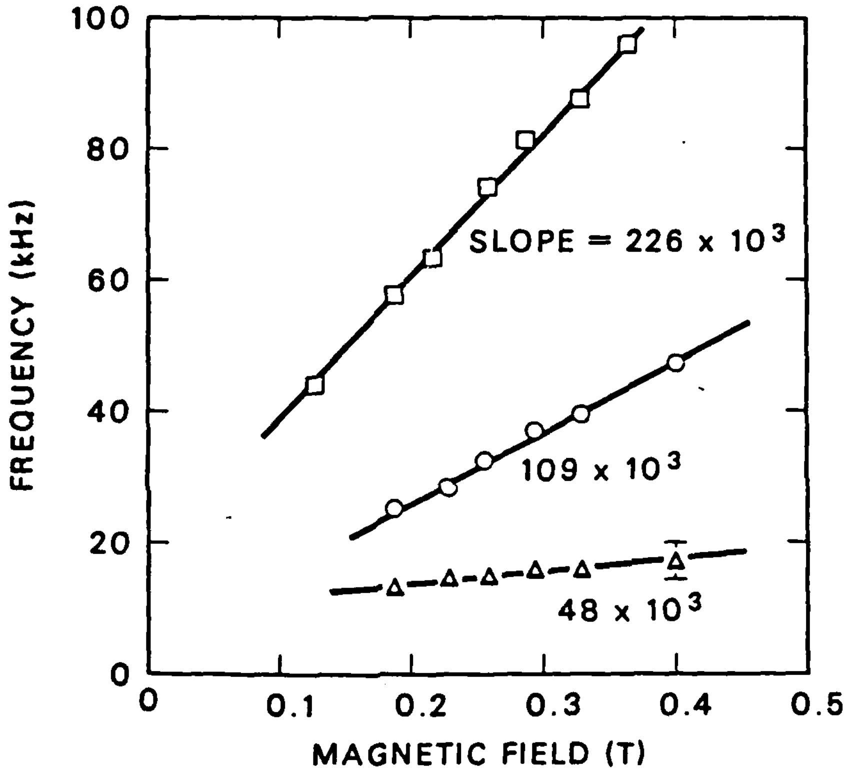


Figure 4.5. Frequency spectra of turbulence vs magnetic field strength.

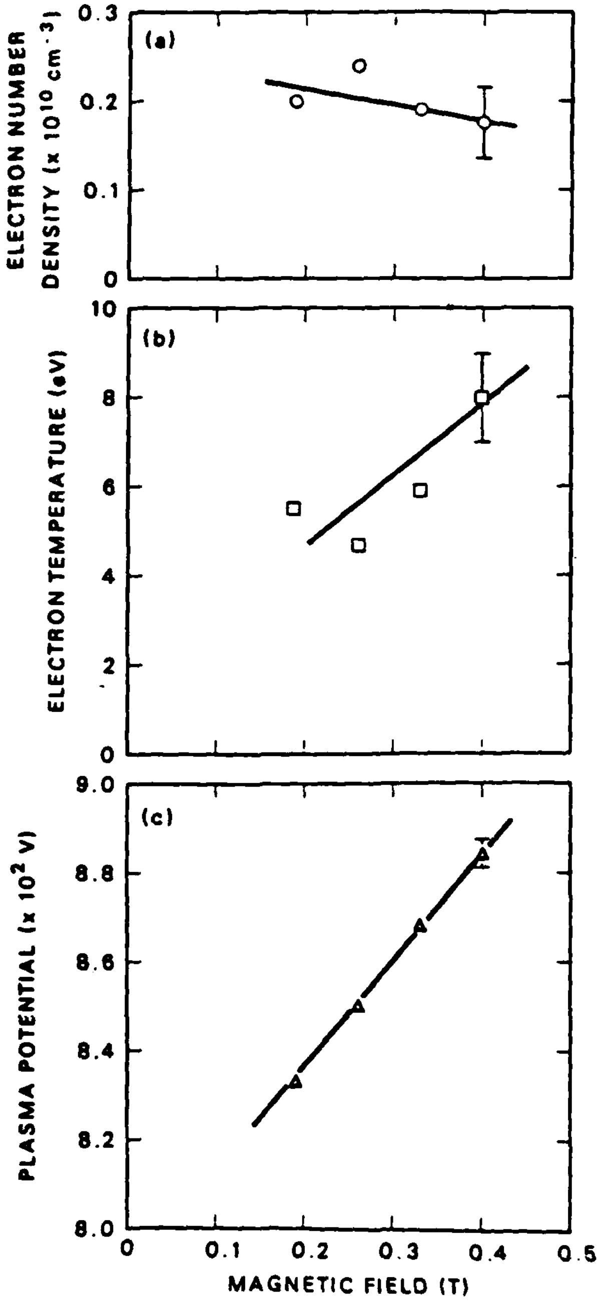


Figure 4.6. Plasma parameters as a function of magnetic field strength.

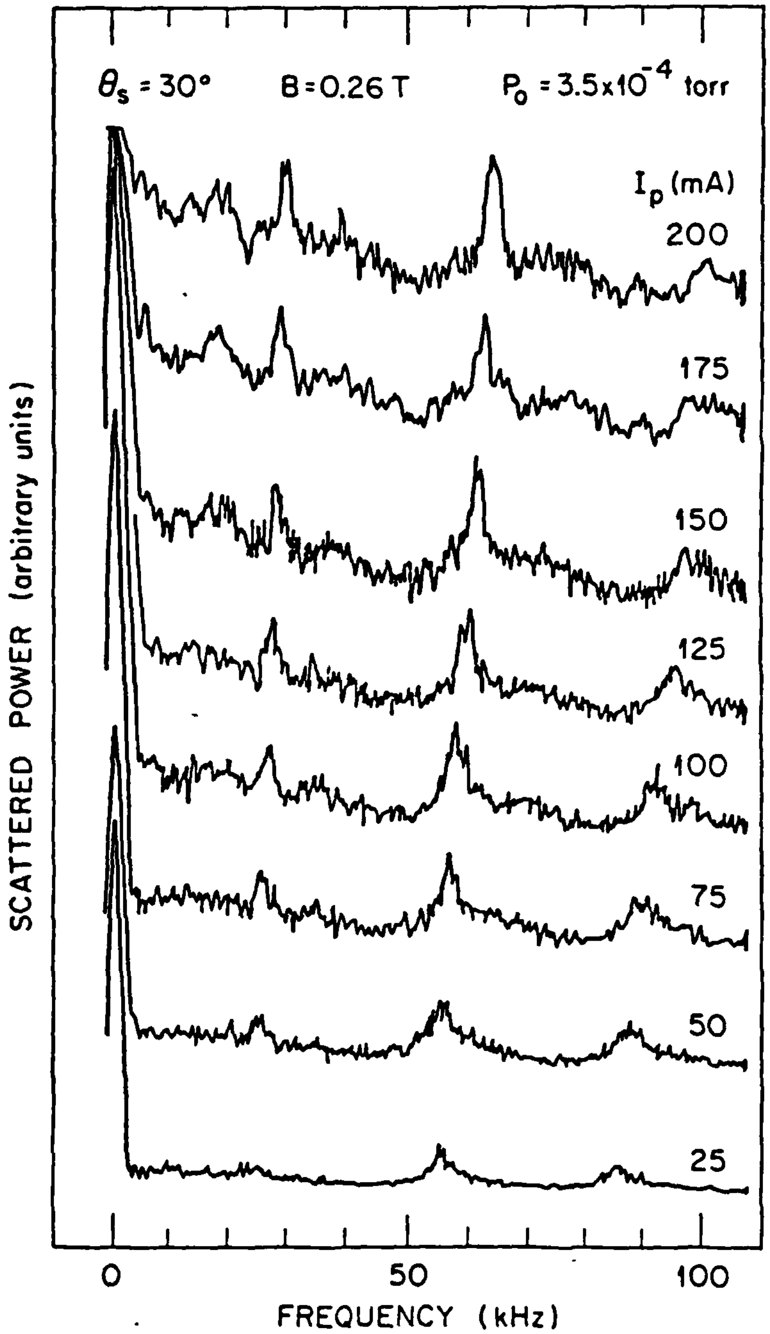


Figure 4.7. Dependence of turbulence frequency spectra on plasma current.

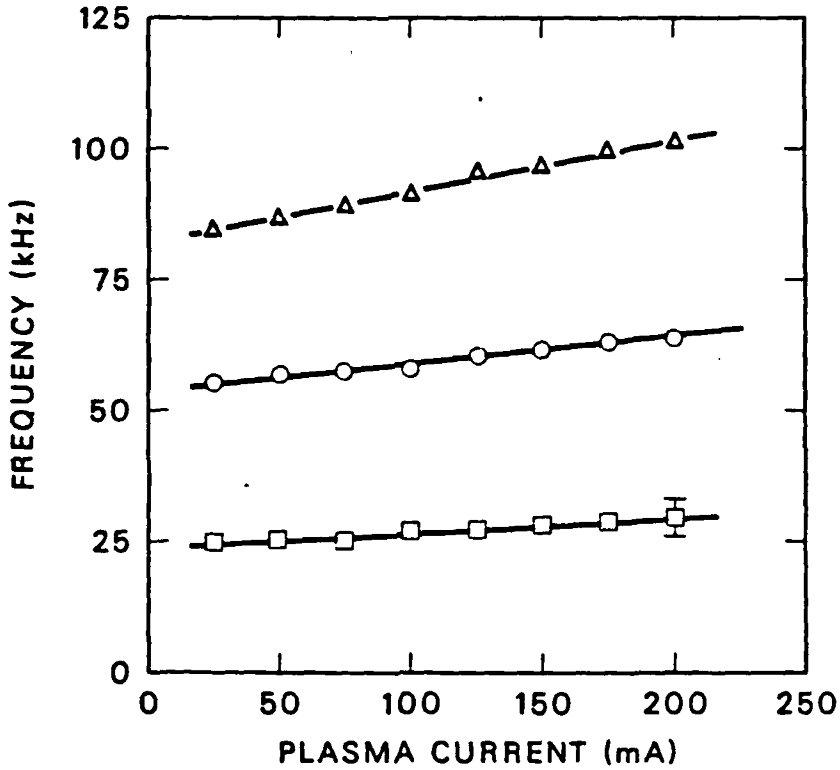


Figure 4.8. Frequency of peak in turbulent spectra as a function of plasma current.

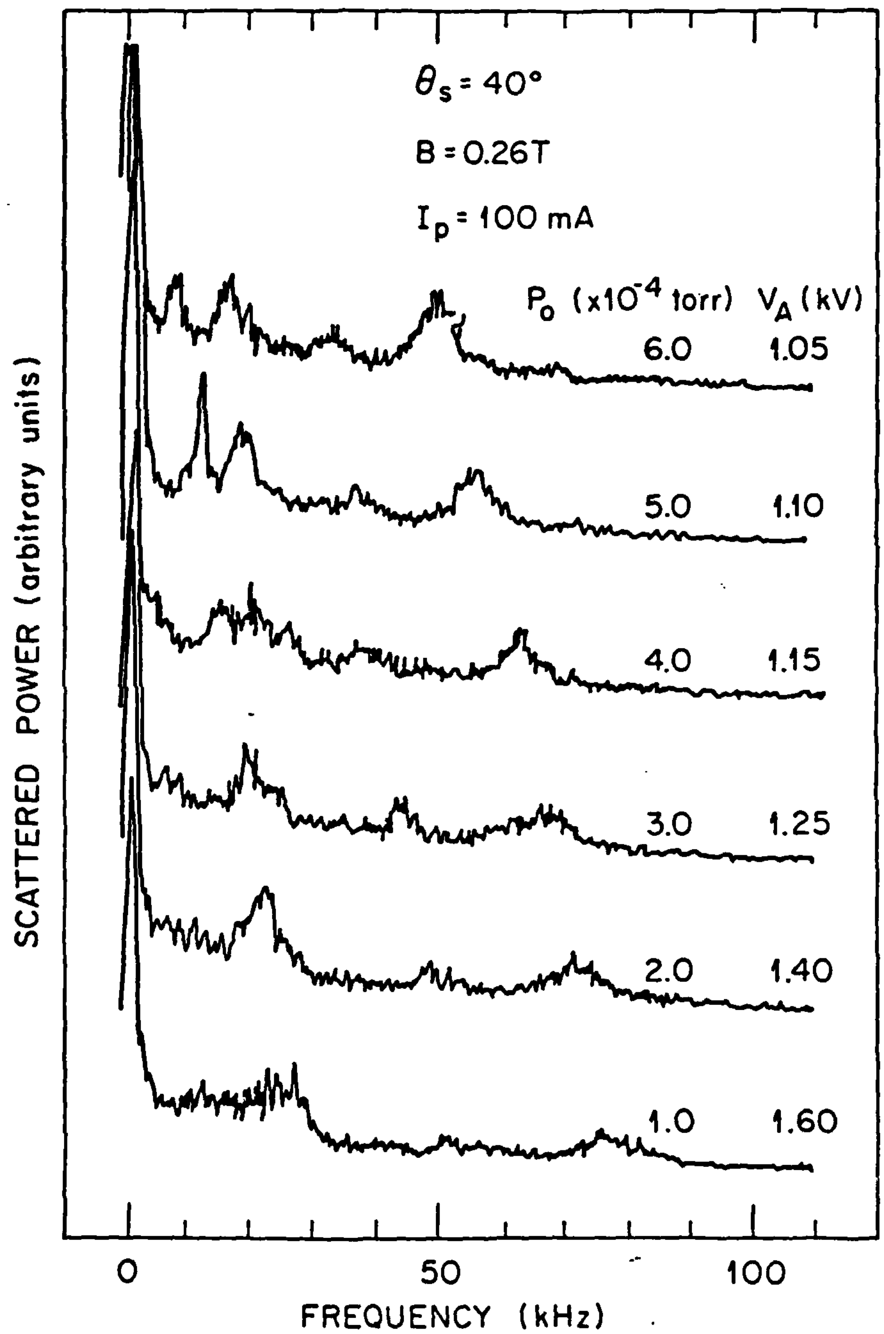


Figure 4.10. Dependence of turbulence frequency spectra on anode voltage.

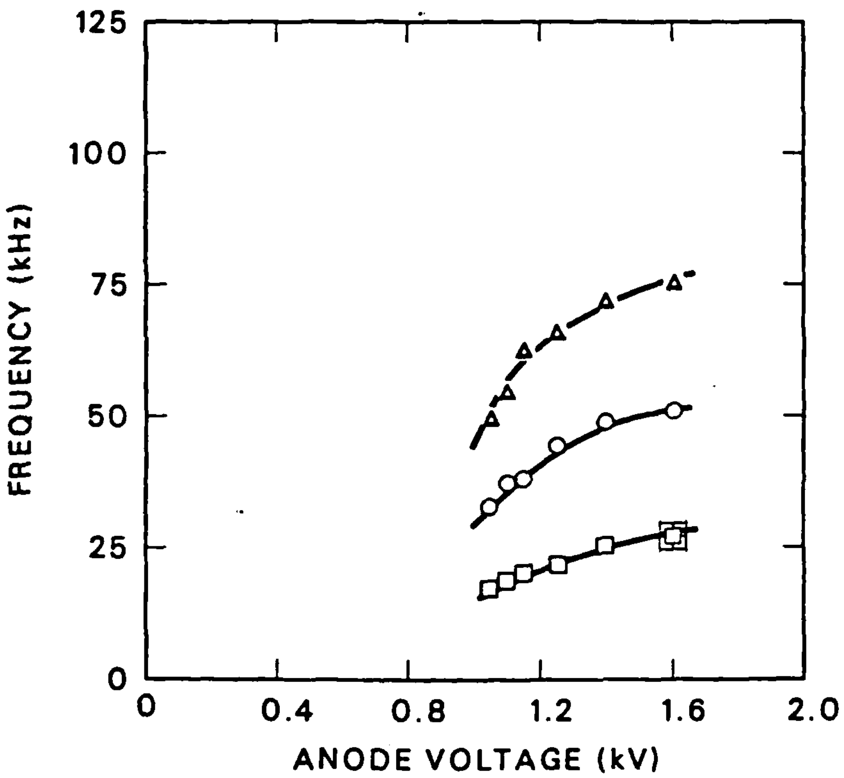
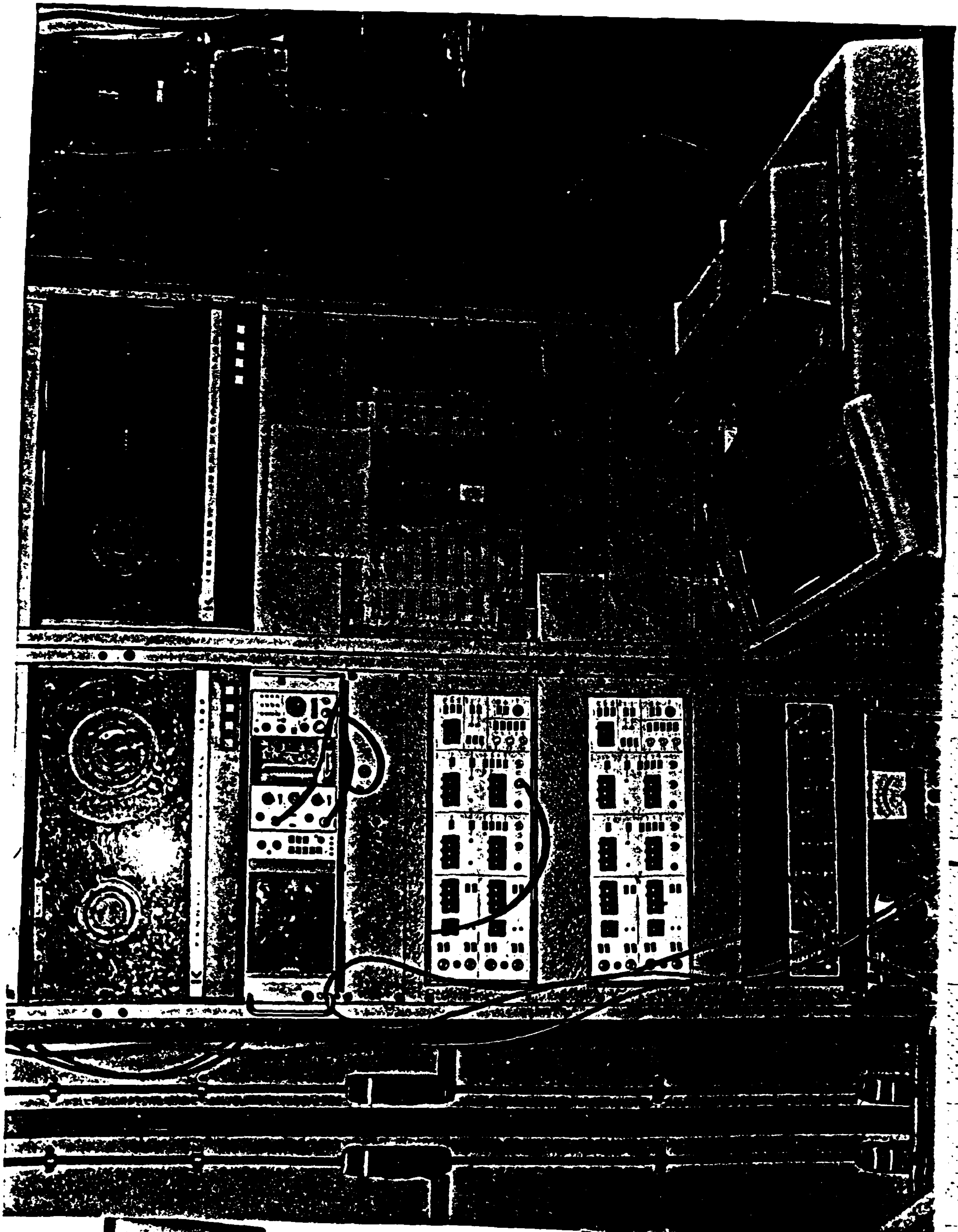
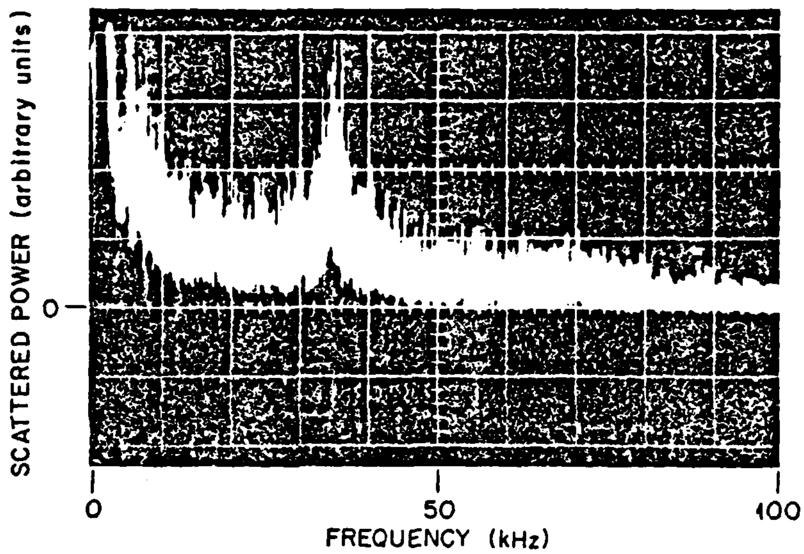


Figure 4.11. Dependence on peak frequency in turbulent spectrum as a function of anode voltage.





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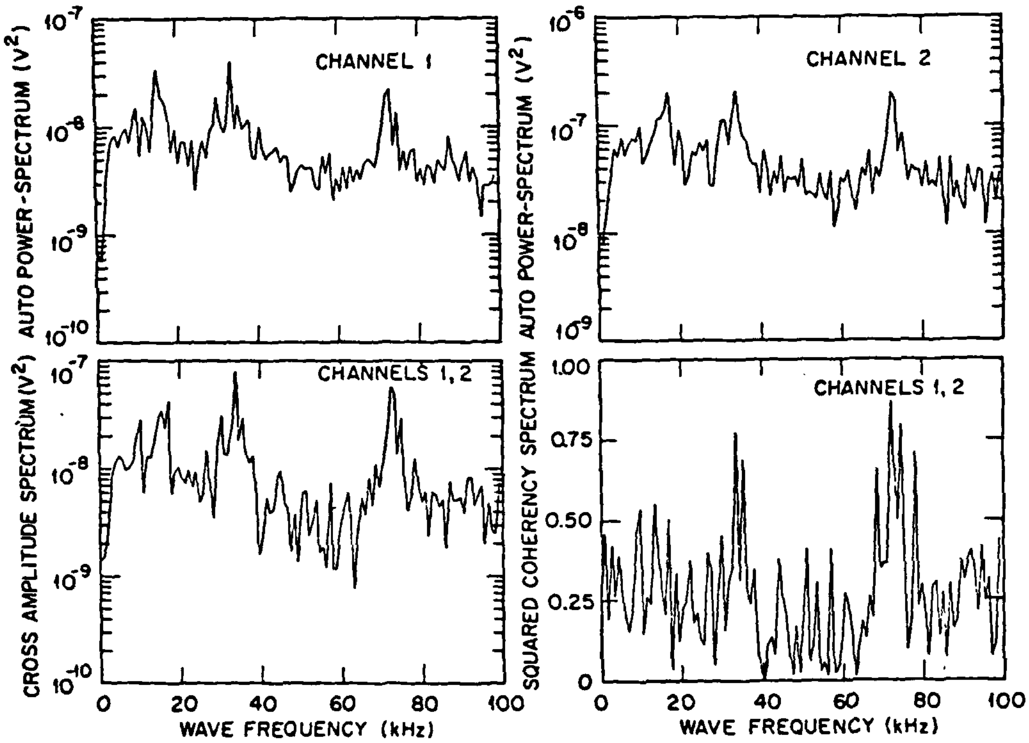


Figure 4.14. Correlation of capacitive probes at the same anode location. B = 0.26 T, P_o = 3.5 × 10^{-4} torr, I_p = 100 mA.

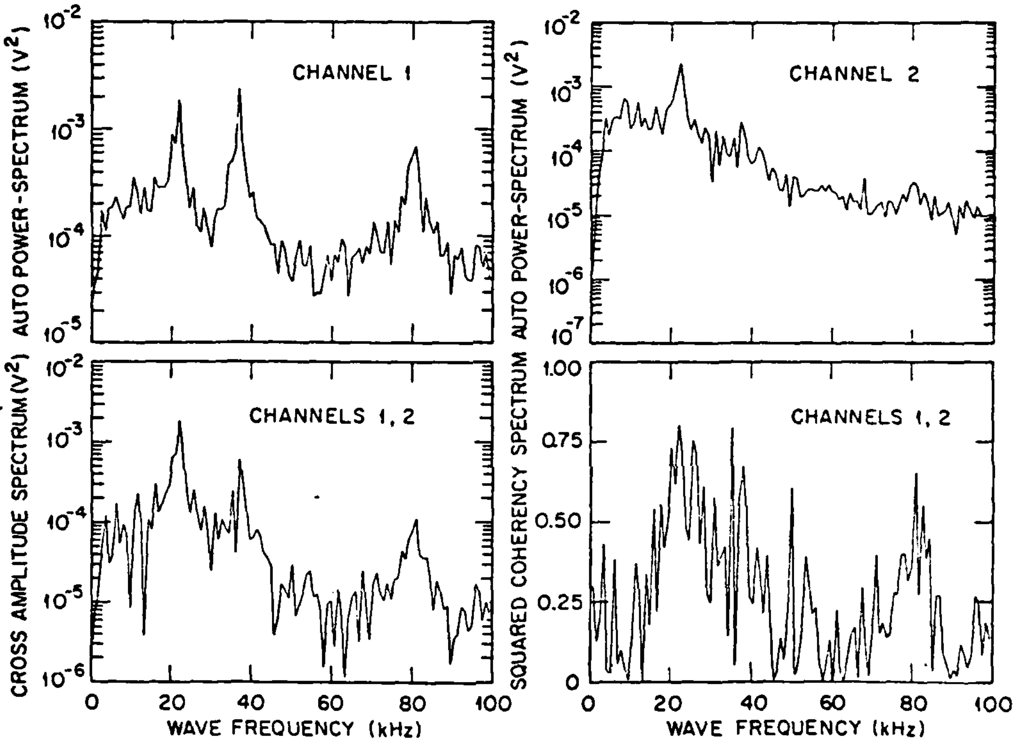


Figure 4.15. Correlation of capacitive probes at anode and cathode locations. Channel 1 is the probe at the anode, and channel 2 is the probe at the cathode. B = 0.26 T, $P_o = 3.5 \times 10^{-4}$ torr, I_p = 100 mA.

Abstract Submitted
For the Twenty-Sixth Annual Meeting
Division of Plasma Physics
October 29 to November 2, 1984

Category Number and Subject 1.11 Electron Beam/Plasma Interactions

☐ Theory ☒ Experiment

Anomalous Drift Waves Detected with Microwave Scattering in an Electric Field Dominated Plasma.* LARRY R. BAYLOR, J. REECE ROTH, PEYMAN DEHKORDI AND MOUNIR LAROUSSI, Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37996-2100.-We have operated a steady-state classical Penning discharge in a uniform axial magnetic field of 0.4 Tesla. The electron number density is typically $2 \times 10^9/cm^3$ in helium gas, with $T_e = 5\text{-}10$ eV. We have applied 32 GHz microwave scattering and capacitive probes in conjunction with a two-channel analog-to-digital data handling system which is capable of producing auto and cross power, phase, and coherence spectra. A strong background of electrostatic turbulence was observed, the RMS values of density of which were as high as several percent of the average electron density. The fluctuation spectrum exhibited several peaks between 10 and 50 kHz, which appeared to be the fundamental and sub-multiples of E/B drift waves, characteristic of Penning discharges (1). The frequency of this disturbance was proportional to B, implying a radial electric field, the magnitude of which is proportional to B^2.

1. J. R. Roth, P. D. Spence, L. R. Baylor, D. Rosenberg, and P. Dehkordi, Paper P1-12, 1984 Int. Conf. on Plasma Physics, Lausanne, Switzerland, June 1984.

*Supported by contract AFOSR 81-0093.

PAPER IW-4

ANAMALOUS DRIFT WAVES DETECTED WITH MICROWAVE SCATTERING IN AN ELECTRIC FIELD DOMINATED PLASMA*

MOUNIR LAROUSSI, LARRY R. BAYLOR, PEYMAN DEHKORDI AND J. REECE ROTH

UTK PLASMA SCIENCE LABORATORY
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF TENNESSEE
KNOXVILLE, TENNESSEE 37996-2100

Presented at the Twenty-Sixth Annual Meeting
of the APS Division of Plasma Physics
Boston, Massachusetts, Oct. 29 to Nov. 2, 1984

APS Bulletin 29, No. 8, p. 1197 (1984)

*Supported by AFOSR contract 81-0093.

THE CLASSICAL PENNING DISCHARGE

WITH UNIFORM AXIAL MAGNETIC FIELD

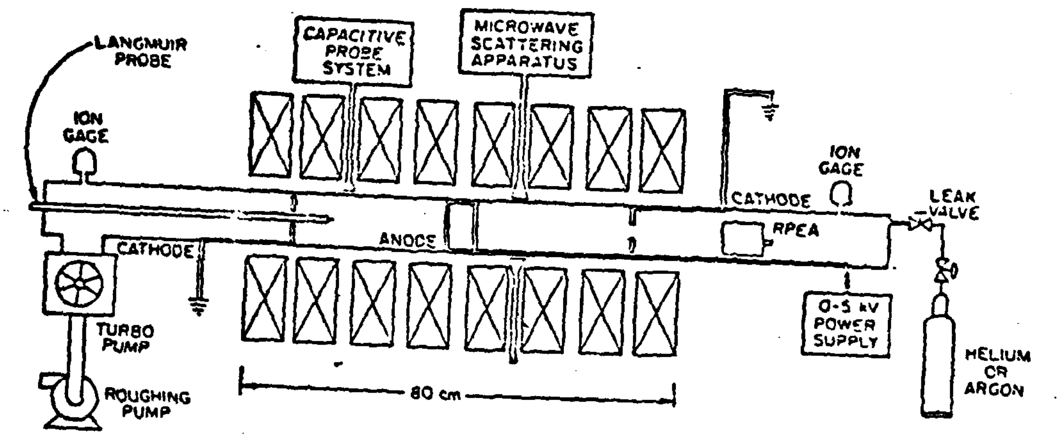
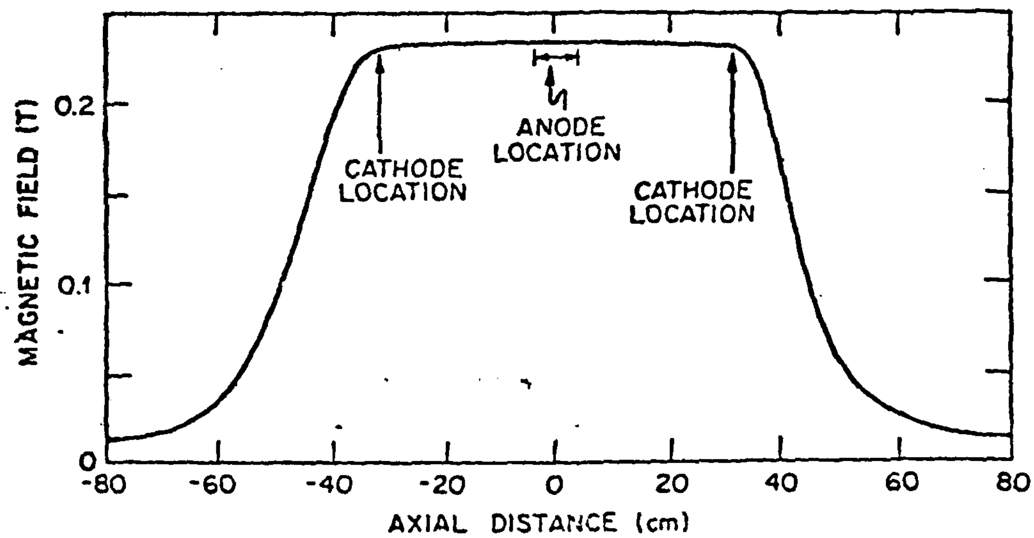


Figure 3.1. Penning discharge schematic.



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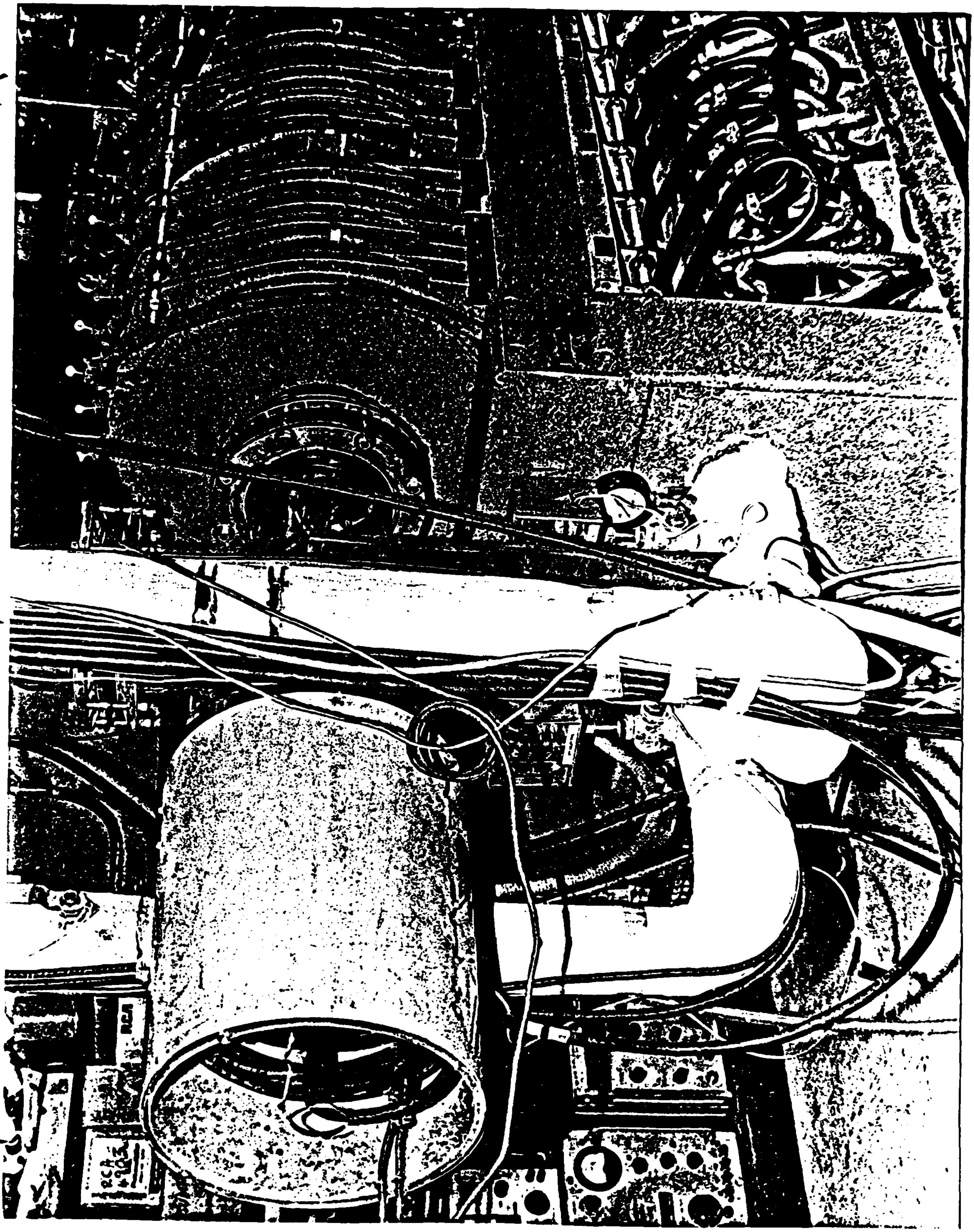

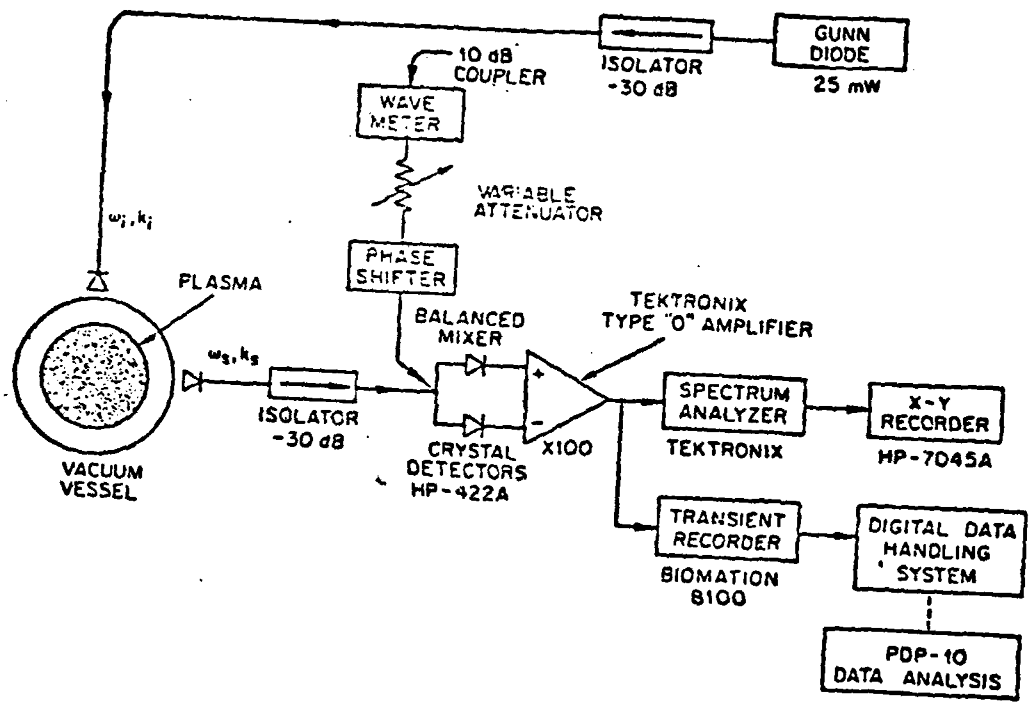

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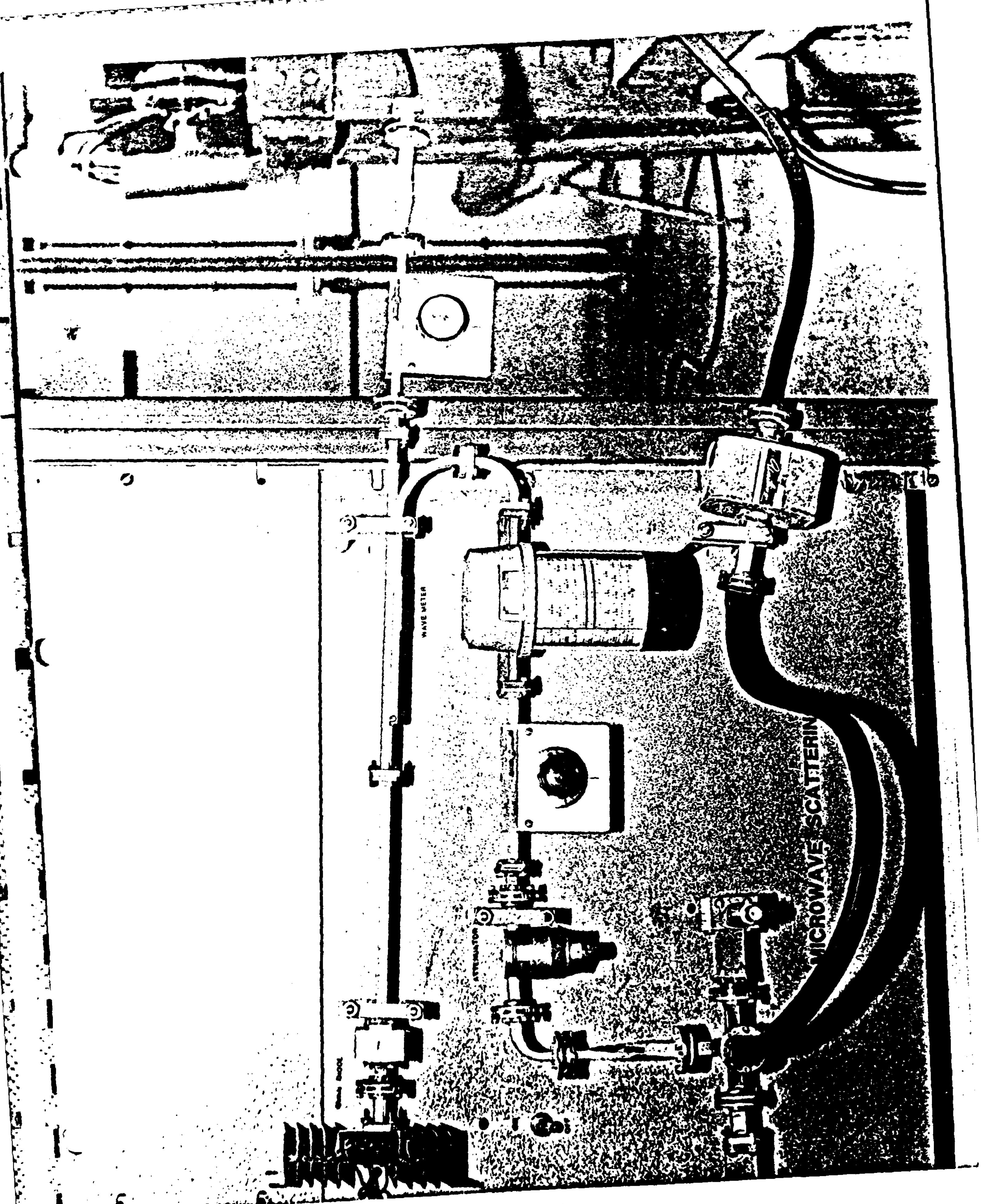
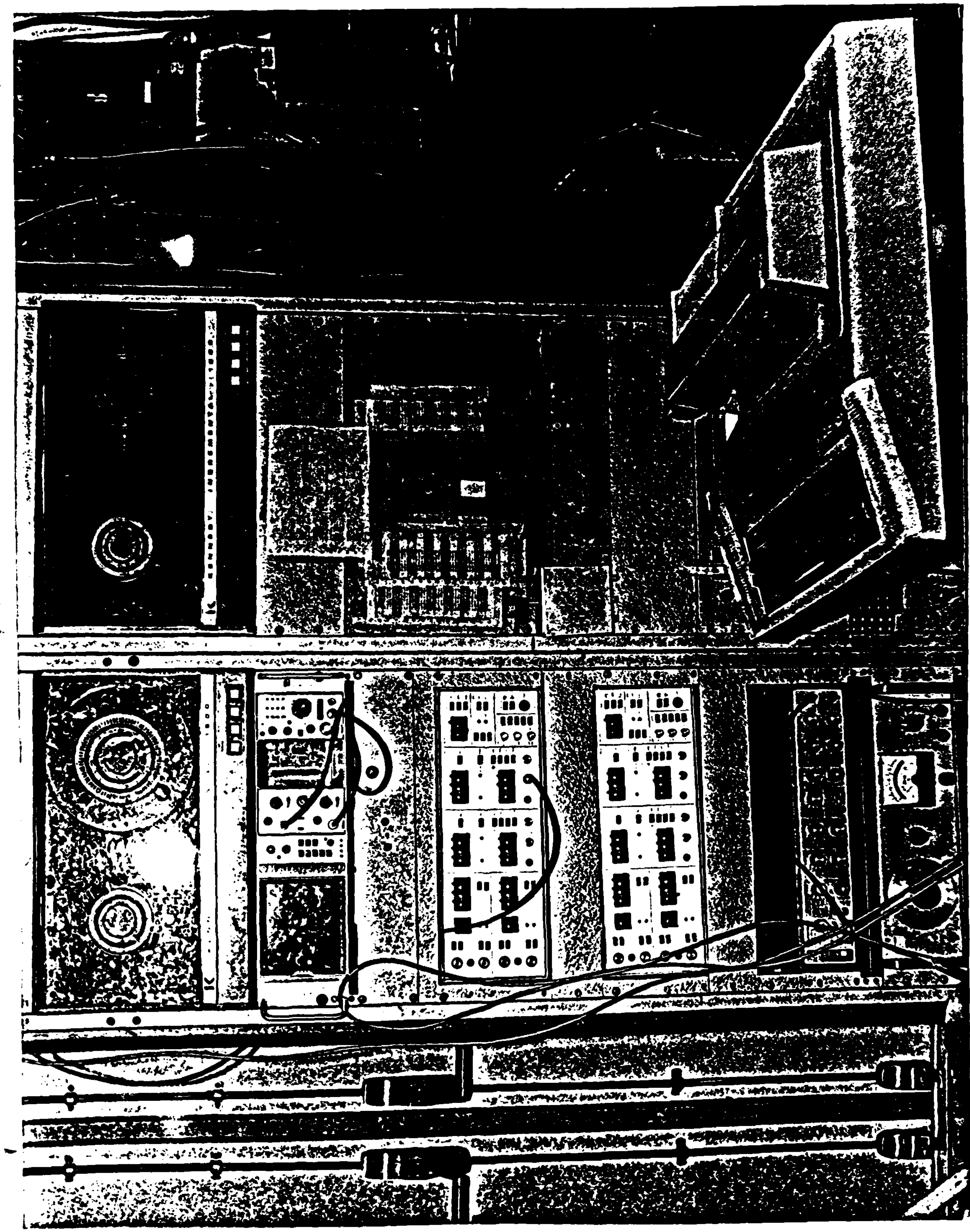
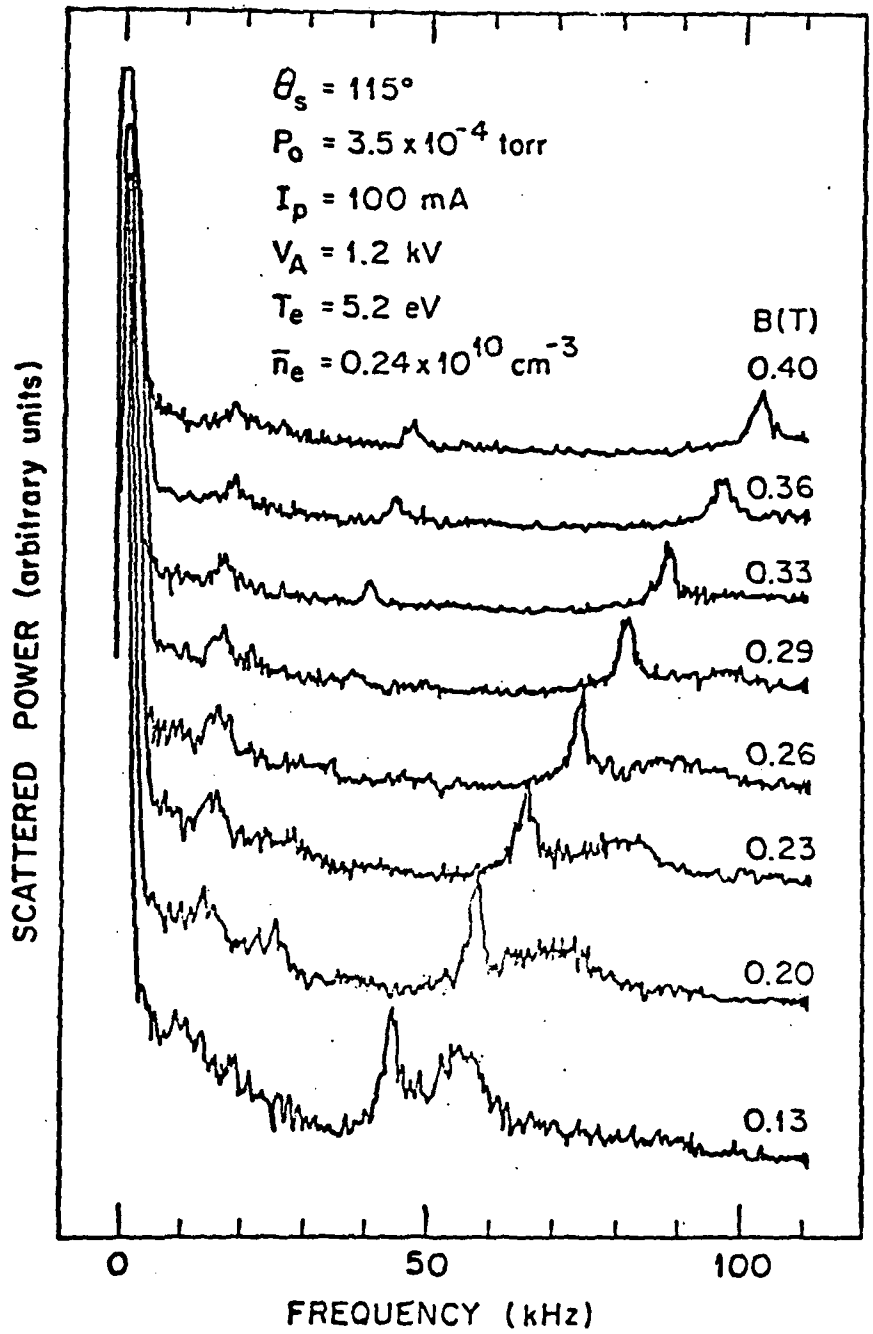

MICROWAVE SCATTERIN
WAVE METER





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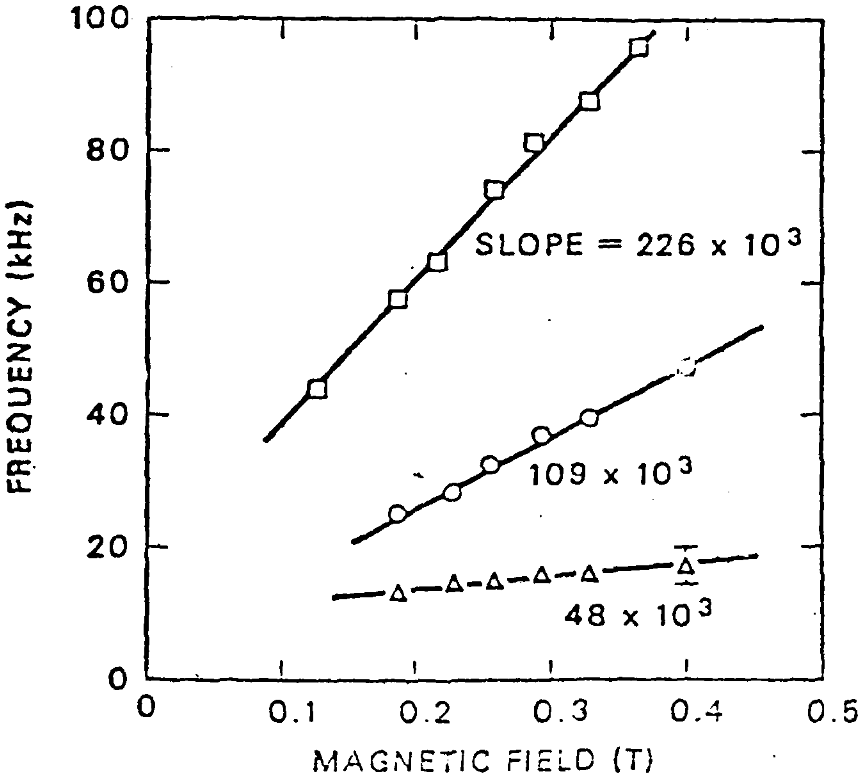

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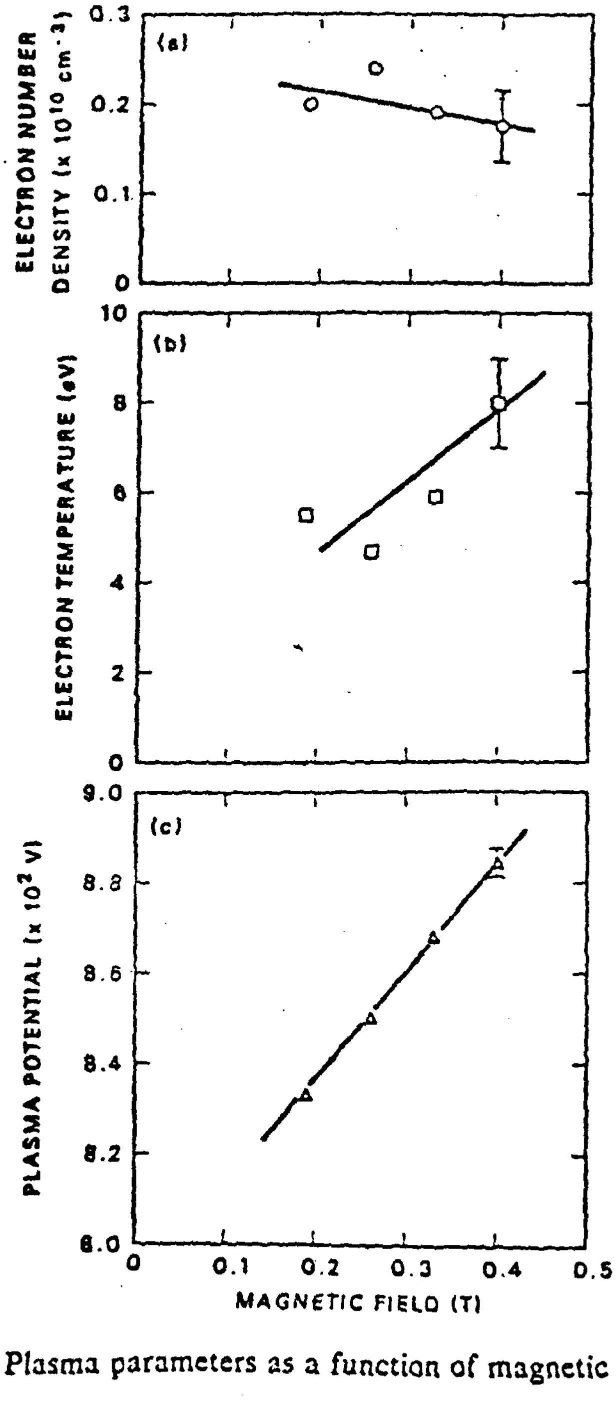

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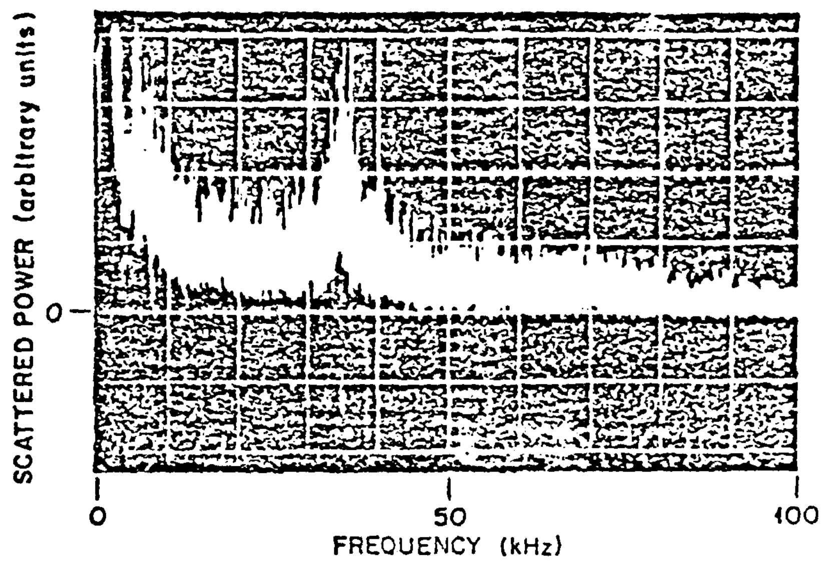

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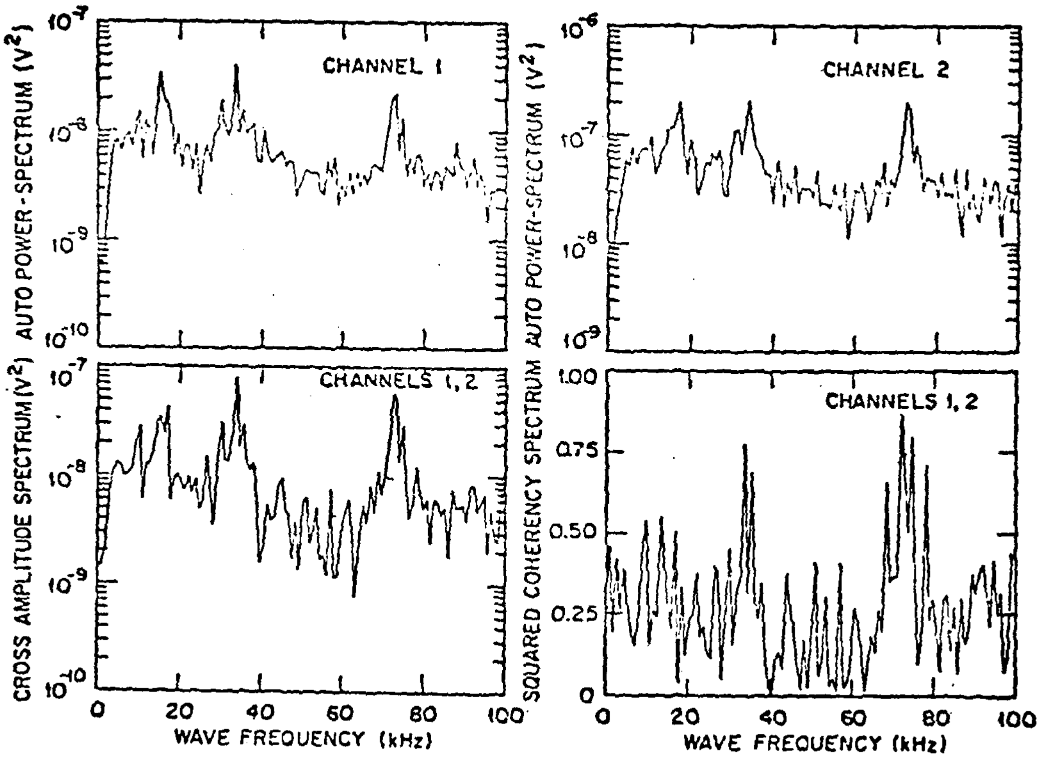

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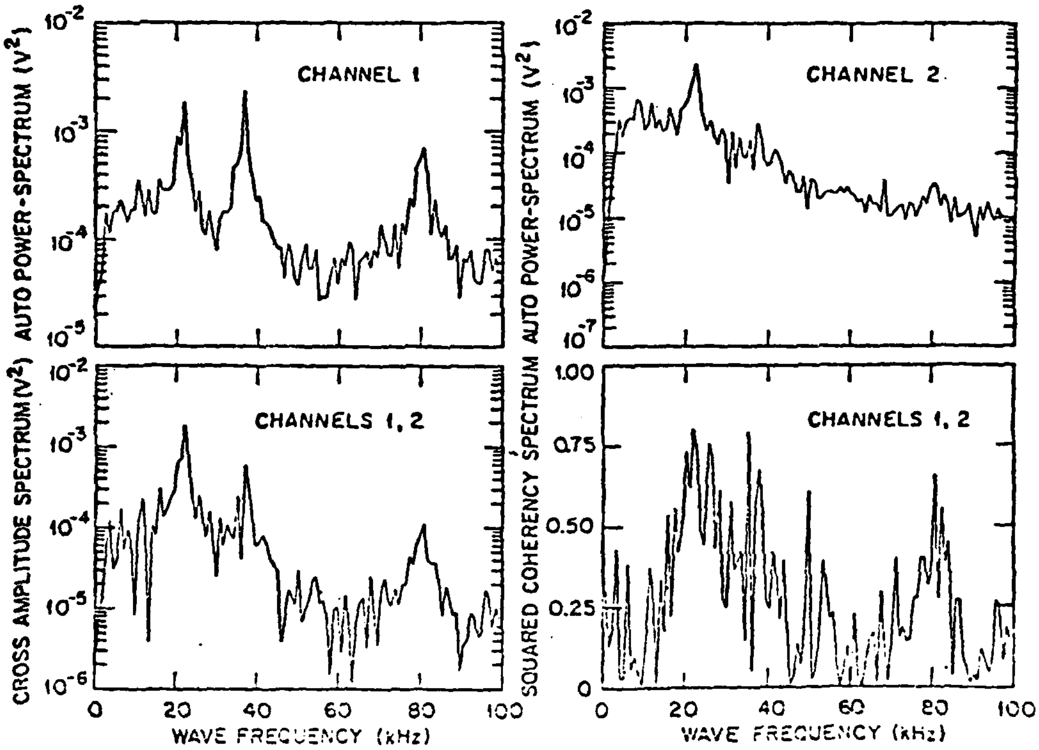

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M-AVERAGE=9
WINDOW: COS BELL
ANODE VOLTAGE:01.3 KV
PLASMA CURRENT:0.056 AMP
MAGNETIC FEILD:0.262 TESLA
NETURAL PRESSURE:0190.0 M-TORR
SCATTERING ANGLE:999.0 DEGREE
2CAPPRO- 1 AT ANODE -2 AT 90 D
EGREES

V_F = 1050v

T_e = 8.36 eV

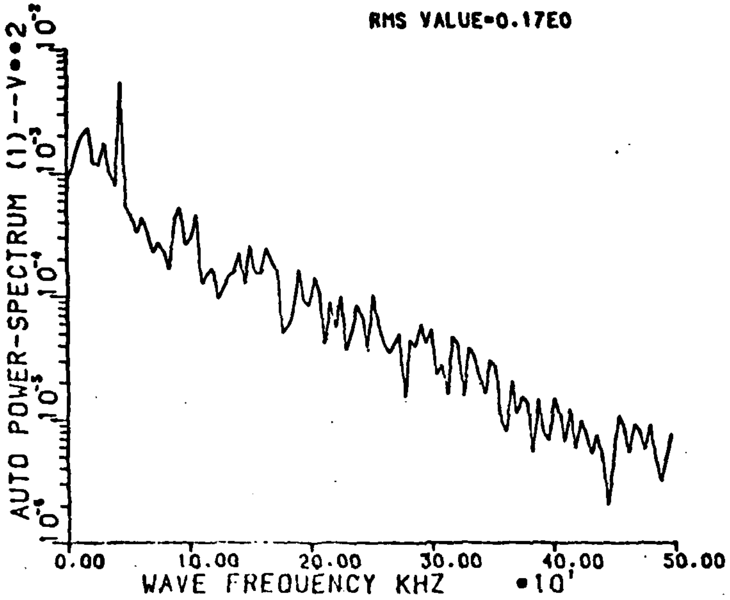
T_i = 550 eV

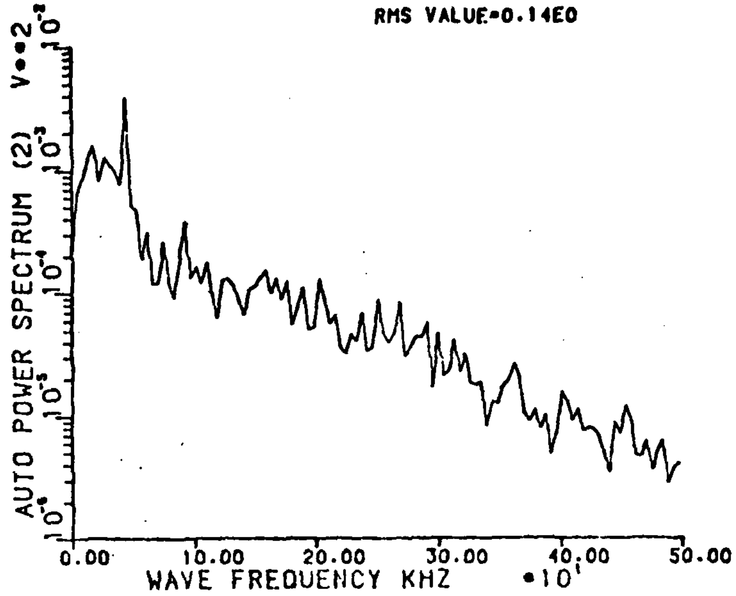
n = 1.35 10^9 cm^{-3}

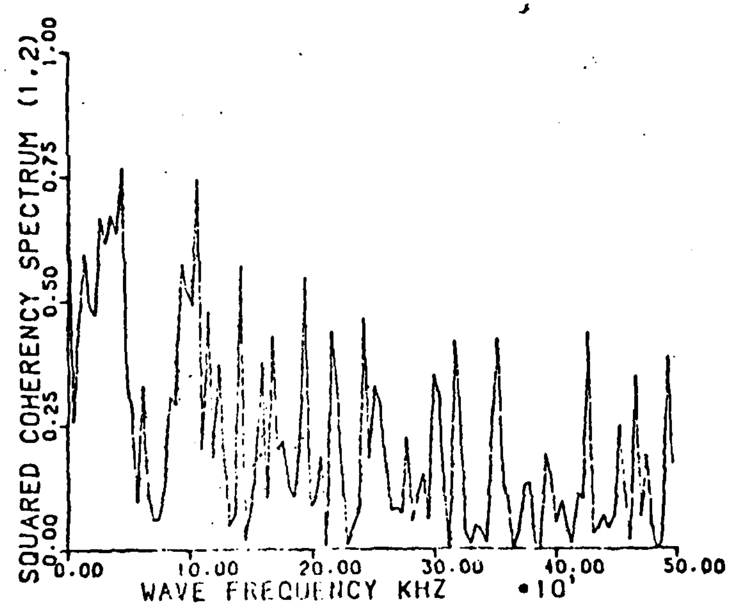
ν_{pe} = 320 MHz

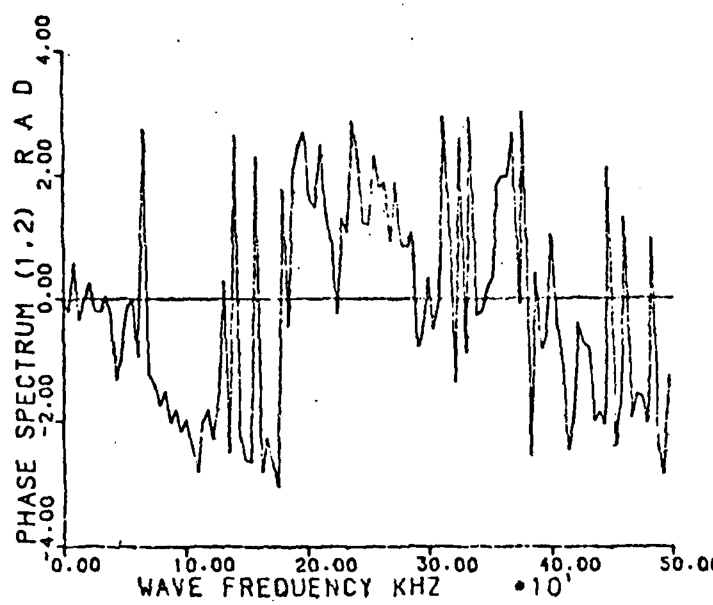
J_{ph} = 19.59 10^3 ms^{-1}

E = 513 V cm^{-1}









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ANODE VOLTAGE:01.3 KV
PLASMA CURRENT:0.058 AMP
MAGNETIC FEILD:0.300 TESLA
NETURAL PRESSURE:0210.0 M-TORR
SCATTERING ANGLE:999.0 DEGREE
2CAPPRO- 1 AT ANODE -2 AT 90 D
EGREES

V_F = 1010 v

T_e = 122 eV

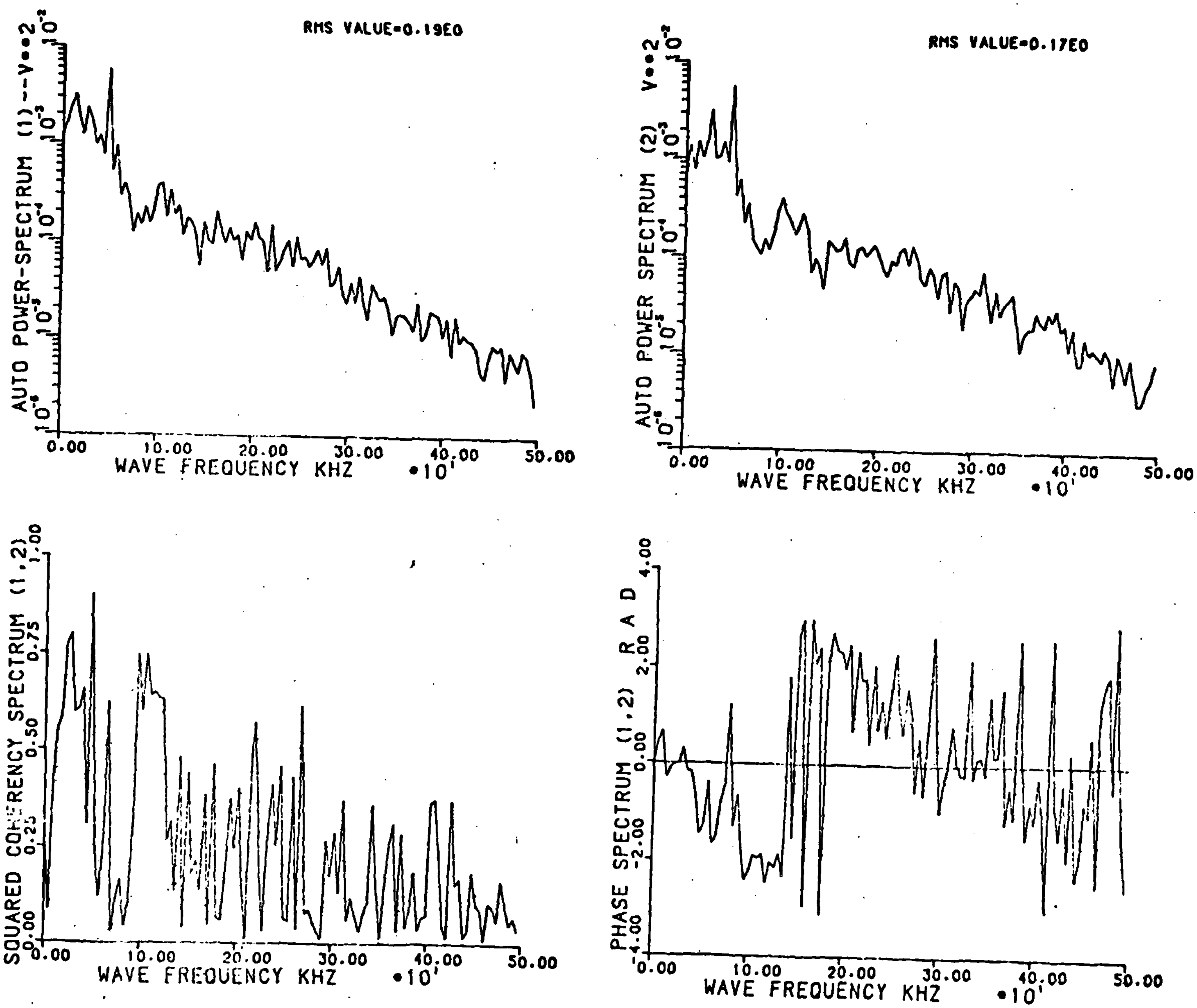
T_i = 122 eV

$n = 1.54 \times 10^9\ cm^{-3}$

ω_{pe} = 340 MHz

$U_{ph} = 19.58\ 10^3\ ms^{-1}$

$E = 587\ V\ cm^{-1}$



DATE: 10/18/84
FILE NUMBER= 08
RUN NUMBER= AOM1
SAMPLING TIME=1.00 MS
SPECTRAL BANDWIDTH=4.39 KH Z
M-AVERAGE=9
WINDOW: COS BELL
ANODE VOLTAGE:01.3 KV
PLASMA CURRENT:0.056 AMP
MAGNETIC FEILD:0.385 TESLA
NETURAL PRESSURE:0240.0 M-TORR
SCATTERING ANGLE:999.0 DEGREE
2 CAP PRO -1 AT ANODE- 2 AT 90
DEGREES

$V_F = 928$ V

$T_e = 11.6$ eV

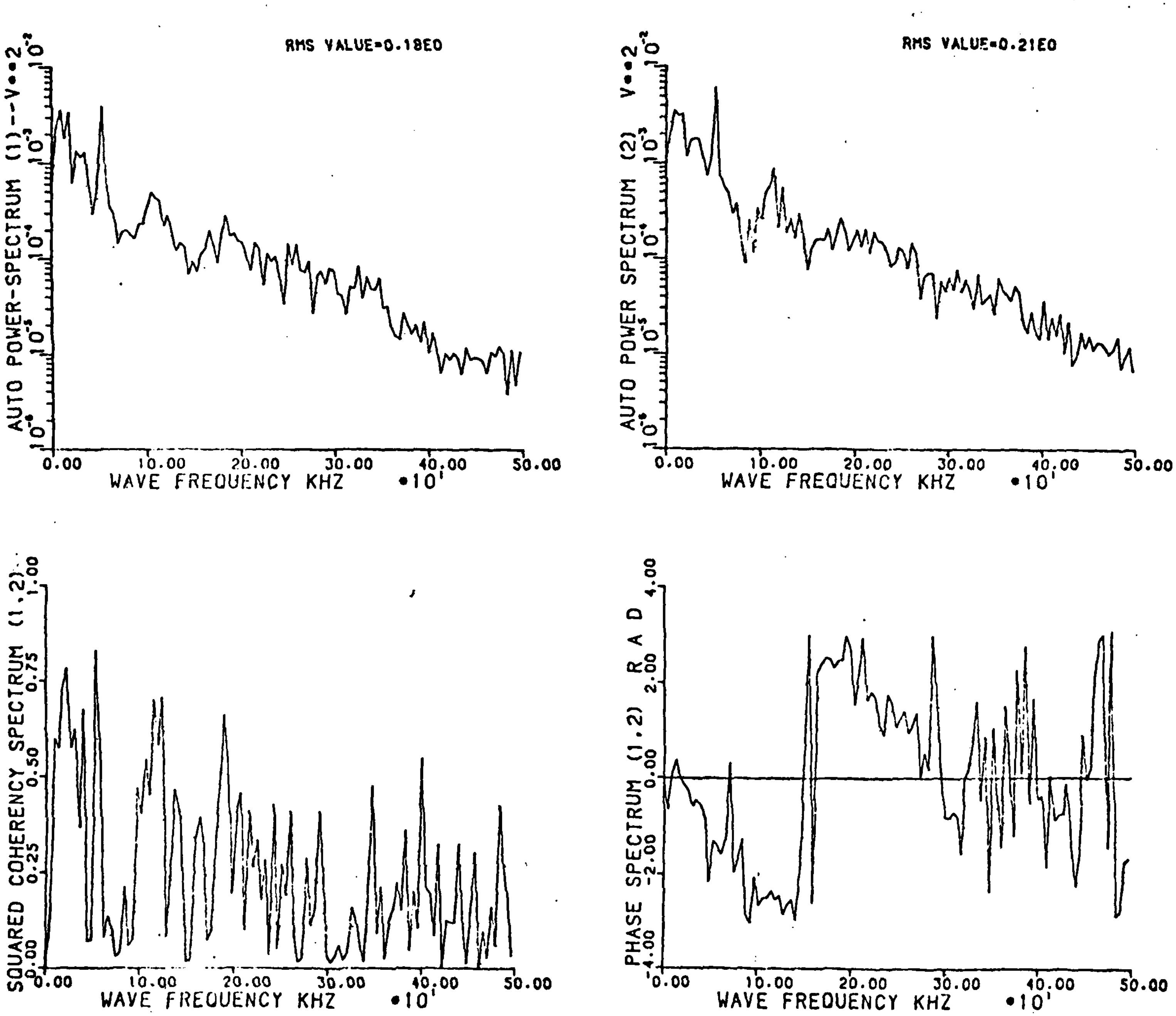
$T_i = 768$ eV

$n = 1.22\ 10^9\ cm^{-3}$

$\nu_{pe} = 300$ MHz

$v_{ph} = 2.5\ 10^4\ ms^{-1}$

$E = 9\ 62.5$ V cm^{-1}



DATE: 10/19/84
FILE NUMBER= 06
RUN NUMBER= A005
SAMPLING TIME=1.00 MS
SPECTRAL BANDWIDTH=4.39 KH Z
M-AVERAGE=9
WINDOW: COS BELL
ANODE VOLTAGE:01.3 KV
PLASMA CURRENT:0.050 AMP
MAGNETIC FEILD:0.262 TESLA
NETURAL PRESSURE:0240.0 M-TORR
SCATTERING ANGLE:999.0 DEGREE
2CAP PRO- 1 AT ANODE3 -2 AT 18
0 DEGREES

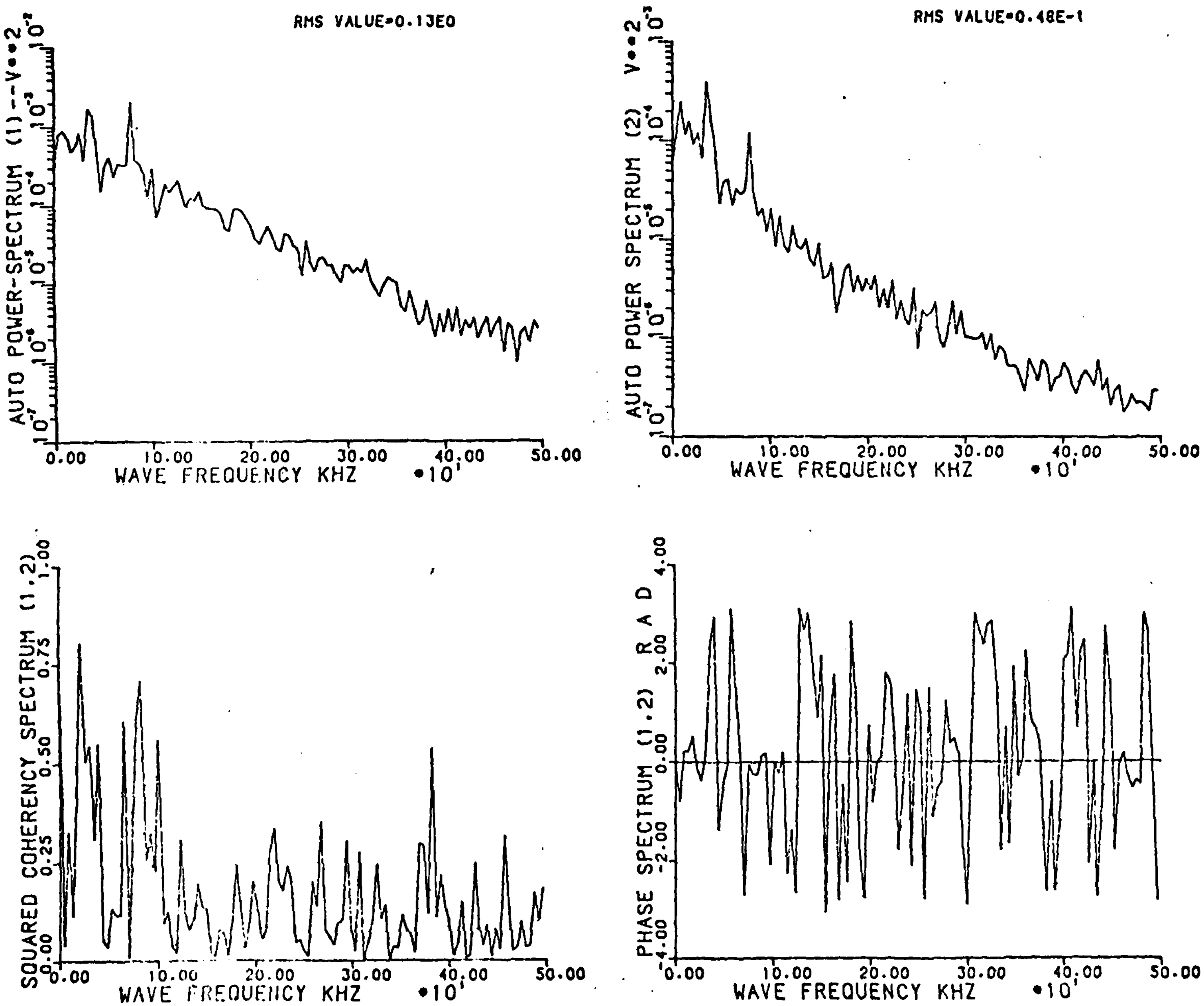
$V_F = 1112V$

$T_e = 5.54\ eV$

$T_i = 1136v$

$n = 1.84\ 10^9\ cm^{-3}$

$\omega_{pe} = 380\ MHz$



DATE: 10/18/84
FILE NUMBER= 02
RUN NUMBER= AON1
SAMPLING TIME=1.00 MS
SPECTRAL BANDWIDTH=4.39 KH Z
M-AVERAGE=9
WINDOW: COS BELL
ANODE VOLTAGE:01.3 KV
PLASMA CURRENT:0.058 AMP
MAGNETIC FEILD:0.300 TESLA
NETURAL PRESSURE:02:0.0 M-TORR
SCATTERING ANGLE:999.0 DEGREE
2 CAP PRO- 1 AT ANODE- 2 AT 26 CM

V_F = 1010 v

T_e = 9.55 eV

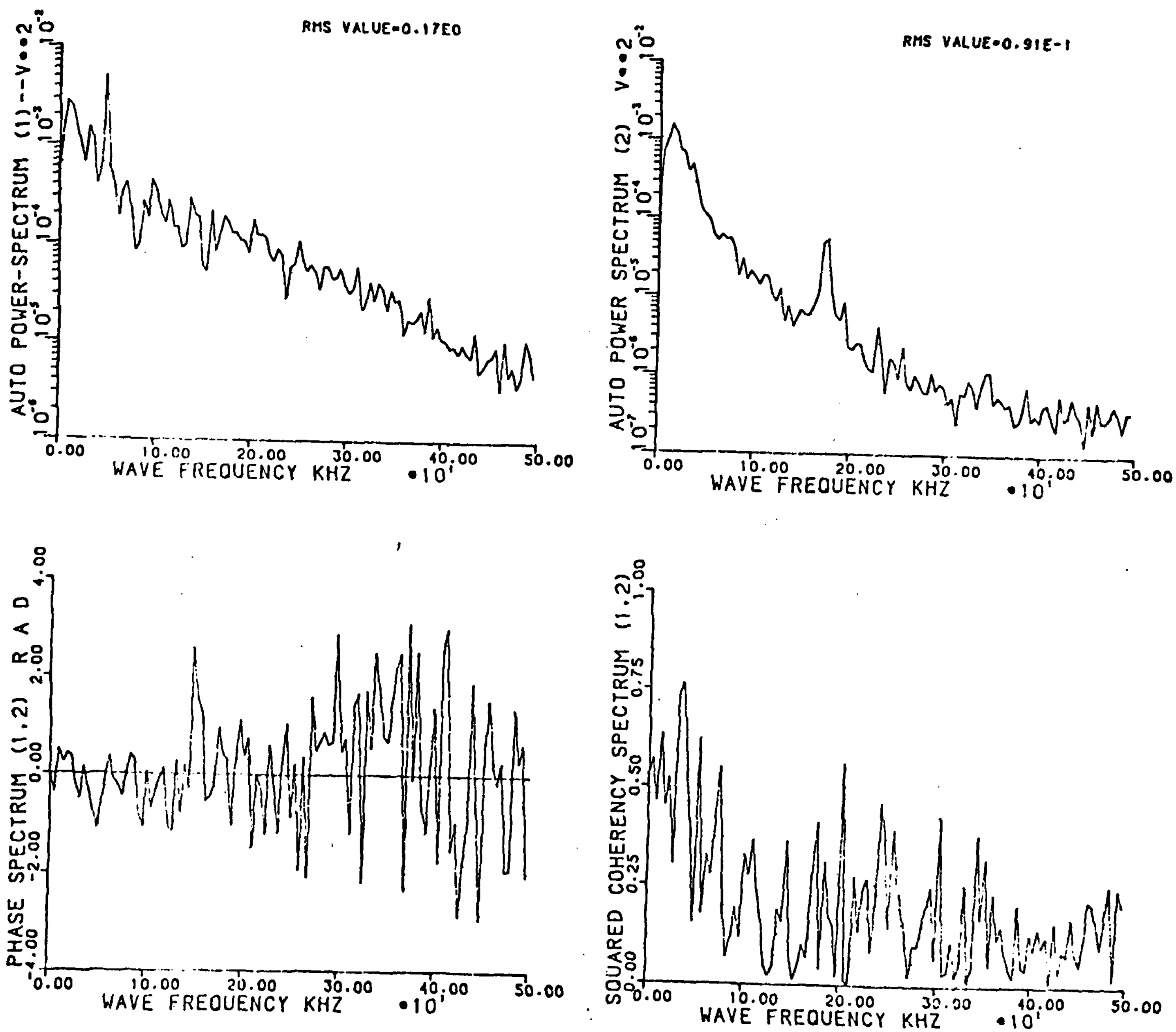
T_i = 122 eV

n = 1.54×10^9 cm^{-3}

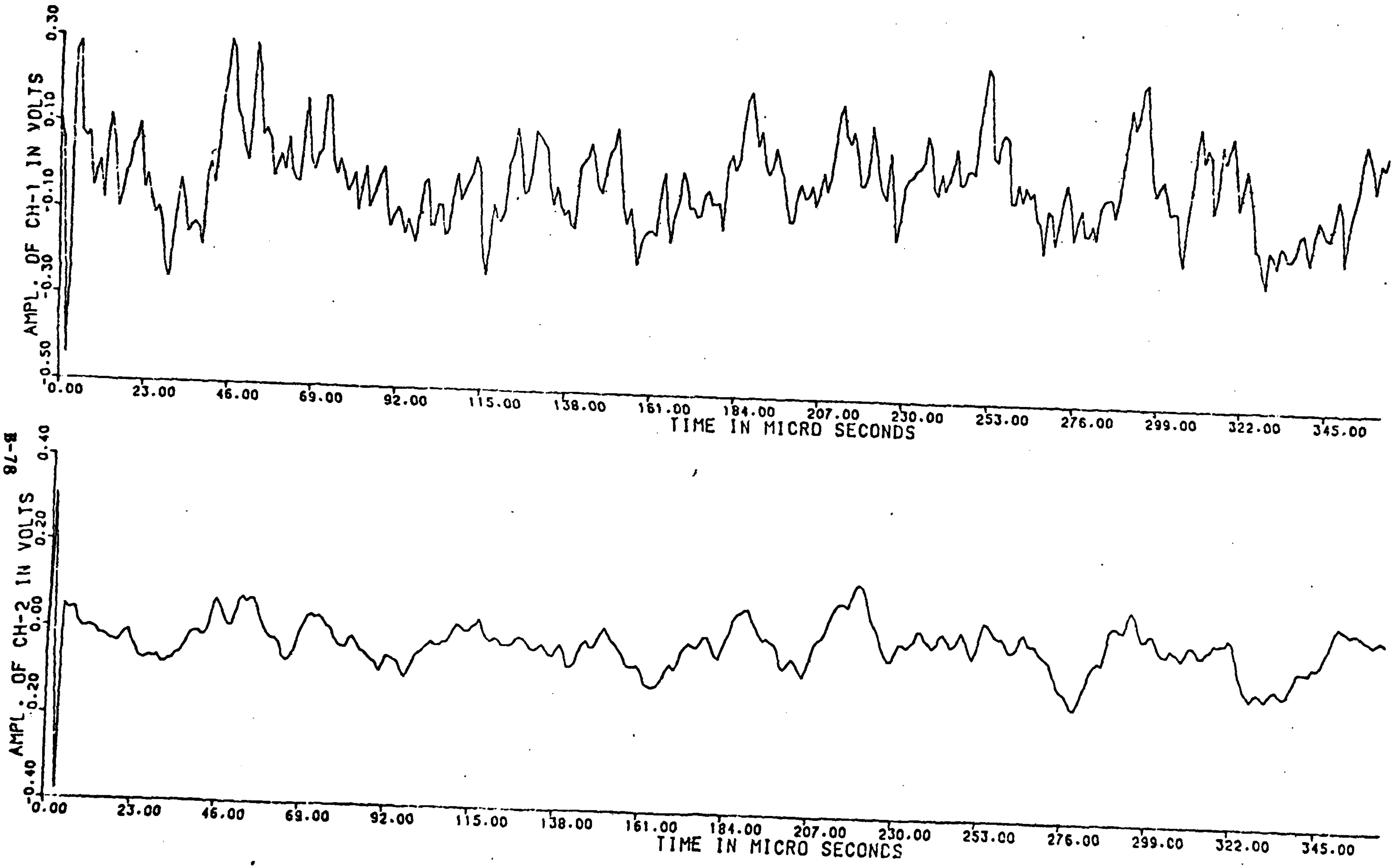
ω_{pe} = 340 MHz

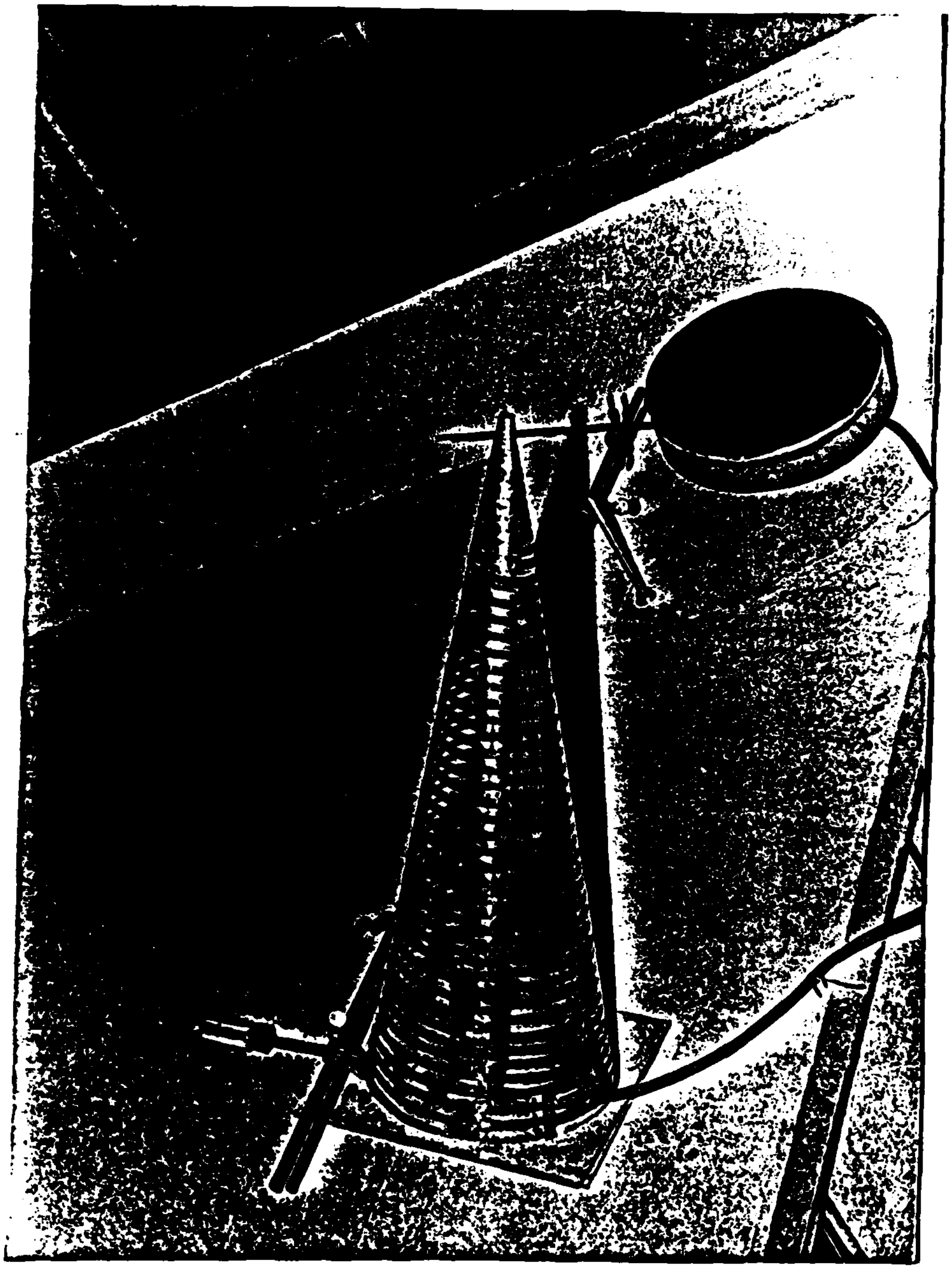
U_{ph} = $19.58\ 10^3$ ms^{-1}

E = 587 V cm^{-1}

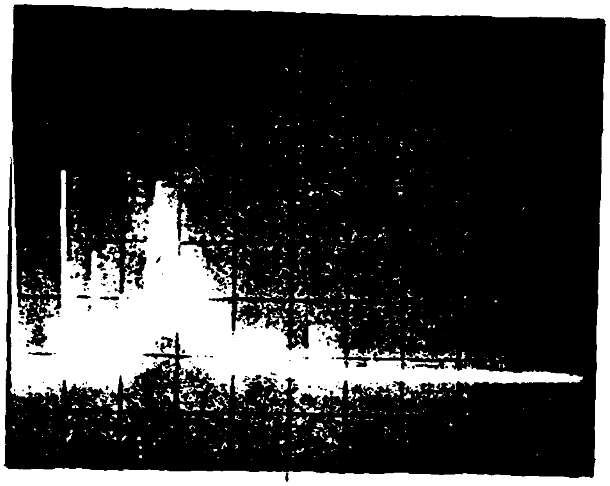


RUN # AOQ5


AMPL. OF CH-1 IN VOLTS
0.30
0.10
-0.10
-0.30
-0.50
0.00
23.00
46.00
69.00
92.00
115.00
138.00
161.00
184.00
207.00
230.00
253.00
276.00
299.00
322.00
345.00
TIME IN MICRD SECONDS
AMPL. OF CH-2 IN VOLTS
0.40
0.20
0.00
-0.20
-0.40
0.00
23.00
46.00
69.00
92.00
115.00
138.00
161.00
184.00
207.00
230.00
253.00
276.00
299.00
322.00
345.00
TIME IN MICRO SECONDS



RF SPECTRUM AS MEASURED BY A PLANAR SPIRAL ANTENNA

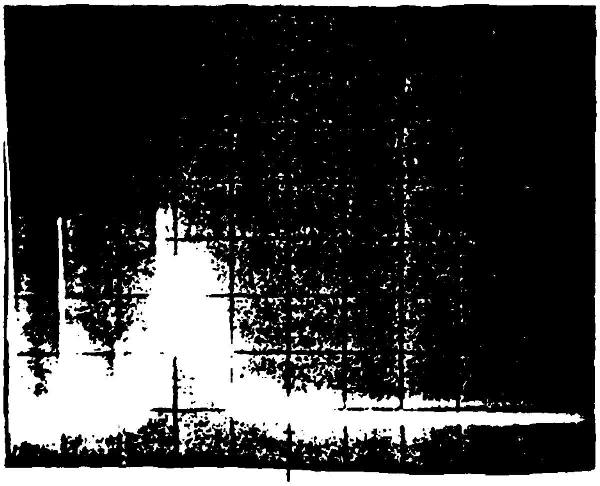


500 MHz

40 μV/div
100 MHz/div
B = 0.385 T
RUN#AOM1

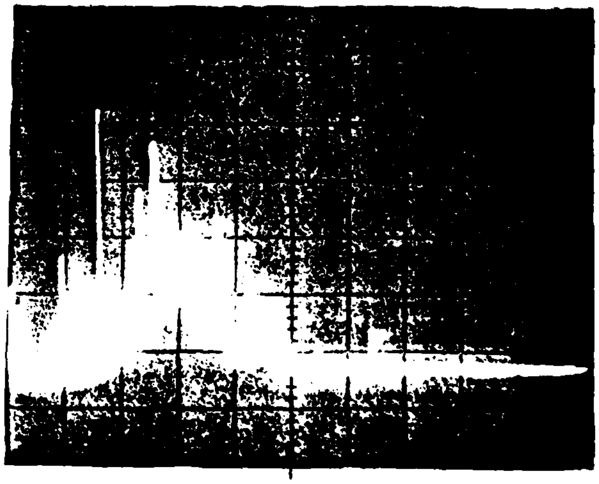
500 MHz

80 μV/div
100 MHz/div
B = 0.3 T
RUN#AON1



500 MHz

80 μV/div
100 MHz/div
B = 0.262 T
RUN#A001



500 MHz

40 MHz/div
100 MHz/div
B = .262 T
RUN#A0Q5

Abstract Submitted
For the Twenty-Sixth Annual Meeting
Division of Plasma Physics
October 29 to November 2, 1984

1W-10 <u>Growing Waves and Electromagnetic Emission from Two Oppositely Directed Electron Beams in a Cold Background Plasma.</u>* --J. REECE ROTH AND IGOR ALEXEFF, <u>University of Tennesee, Knoxville, TN 37996-2100.</u>--We present a generalization of previous theoretical work (1) to the case of two non-relativistic, oppositely directed interpenetrating electron beams of unequal density interacting with a cold background plasma. These conditions can be reduced to a sixth-order cold plasma dispersion relation, which has growing and damped solutions. In the case of two beams, each 1/2 of the total electron density, interacting with cold ions, we recover our previous result (1); growing waves near the geometric mean of the electron and ion plasma frequency. When the beams are much less dense than the cold electron background density, the growing waves are near the electron plasma frequency of the cold electron population. The maximum growth rates are not at the beam electron plasma frequency or at the upper or lower hybrid frequency. The frequency of an oscillator based on this instability can be tuned by adjusting the relative intensity of the two beams as well as the beam density relative to the background plasma.

1.) I. Alexeff, J. R. Roth, J. D. Birdwell, and R. Mallavarpu, <u>Physics of Fluids</u>, 24 (1981) pp1348-57.
*Supported in part by AFOSR contracts 81-0093 and 82-0045, and by ONR contract N00014-80-C-0063.

Paper 1W-10, Monday morning, October 29, 1984
Sheraton-Boston Hotel, Boston, Massachusetts

APS <u>Bulletin</u>, Vol. 29, No. 8, p 1198 (1984)

PAPER IW-10

GROWING WAVES AND ELECTROMAGNETIC EMISSION FROM TWO OPPOSITELY DIRECTED ELECTRON BEAMS IN A COLD BACKGROUND PLASMA*

J. REECE ROTH and IGOR ALEXEFF

UTK PLASMA SCIENCE LABORATORY
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF TENNESSEE
KNOXVILLE, TENNESSEE 37996-2100

Presented at the Twenty-Sixth Annual Meeting
of the APS Division of Plasma Physics
Boston, Massachusetts, Oct. 29 to Nov. 2, 1984

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*Supported in part by AFOSR contracts 81-0093 (Roth) and 82-0045 (Alexeff), and by ONR contract NOOO14-80-C-0063.

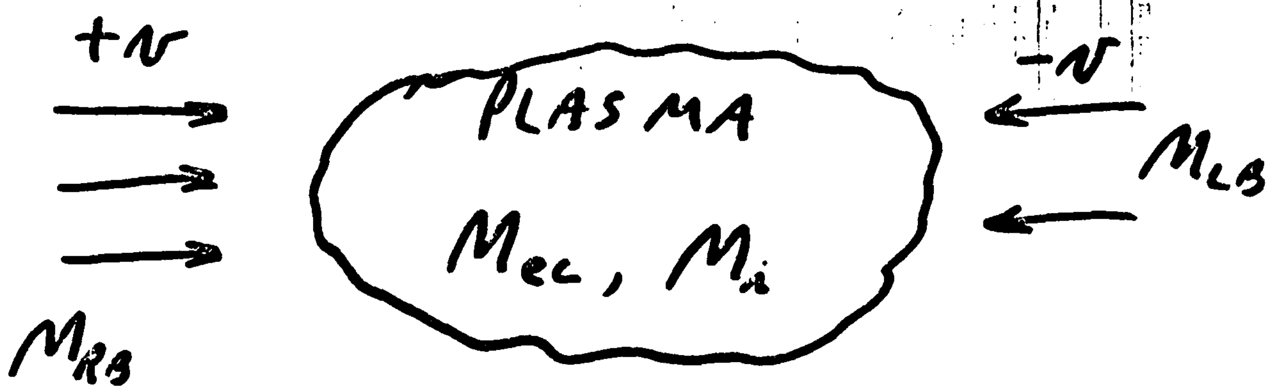
GENERALIZATION OF TWO INTERPENETRATING ELECTRON BEAMS

- Consider the following generalizations of our past work:

1.) Cold ion background plasma, Quasi-neutral.

2.) Cold electron background in beam interaction region.

3.) Beams of unequal densities but equal and opposite speeds in interaction region.



- The following relations will hold:

$$n_e \equiv n_b + n_{ec} = Z n_i \qquad \text{QUASI NEUTRALITY}$$

$$n_B \equiv n_{RB} + n_{LB}$$

$$\alpha \equiv \frac{n_{RB}}{n_B} \; ; \qquad (1-\alpha) \equiv \frac{n_{LB}}{n_B}$$

- The cold plasma dispersion relation is

$$1 = \frac{\omega_{RB}^2}{(\omega - kv)^2} + \frac{\omega_{LB}^2}{(\omega + kv)^2} + \frac{\omega_i^2}{\omega^2} + \frac{\omega_{ce}^2}{\omega^2}$$

- We now define

$$\omega_B^2 \equiv \frac{n_B e^2}{\epsilon_0 m_e}; \quad \omega_{BR}^2 \equiv \frac{n_{BR} e^2}{\epsilon_0 m_e}; \quad \omega_{BL}^2 \equiv \frac{n_{BL} e^2}{\epsilon_0 m_e}$$

$$\omega_e^2 \equiv \frac{n_e e^2}{\epsilon_0 m_e}; \quad \omega_i^2 = \frac{Z n_i e^2}{\epsilon_0 m_i}; \quad \omega_{ce}^2 \equiv \frac{n_{ce} e^2}{\epsilon_0 m_e}$$

- Also,

$$\omega_{BR}^2 = \alpha\, \omega_B^2 ; \qquad \omega_{BL}^2 = (1-\alpha)\, \omega_B^2$$

- The dispersion relation may be written

$$1 = \frac{\alpha\, \omega_B^2}{(\omega - kv)^2} + \frac{(1-\alpha)\, \omega_B^2}{(\omega + kv)^2} + \frac{\omega_i^2 + \omega_{ce}^2}{\omega_B^2}$$

- To facilitate algebraic manipulations, define

$$y \equiv \frac{\omega}{\omega_B}; \qquad x \equiv \frac{kv}{\omega_B}; \qquad \epsilon \equiv \frac{\omega_i^2 + \omega_{ce}^2}{\omega_B^2}$$

- The parameter ϵ can be written

$$\epsilon = \frac{m_e}{M_B}\left(\frac{Z M_i}{m_i} + \frac{M_{ce}}{m_e}\right) = \frac{m_e}{m_i}\frac{M_e}{M_B} + \frac{M_{ce}}{M_B}$$

- Further,

$$\epsilon = \frac{m_e}{m_i}\left(1 + \frac{M_{ce}}{M_B}\right) + \frac{M_{ce}}{M_B} = \frac{m_e}{m_i} + \frac{M_{ce}}{M_B}\left(1 + \frac{m_e}{m_i}\right)$$

<u>STRONG</u> <u>BEAM</u> : $M_B \gg M_{ce}$; $\epsilon \ll 1$

WEAK BEAM : $M_B \ll M_{ce}$; $\epsilon \gg 1$

- The parameter range is

$$0 \leq \epsilon \leq \infty \; ; \quad 0 \leq \alpha \leq 1$$

- The dispersion relation is

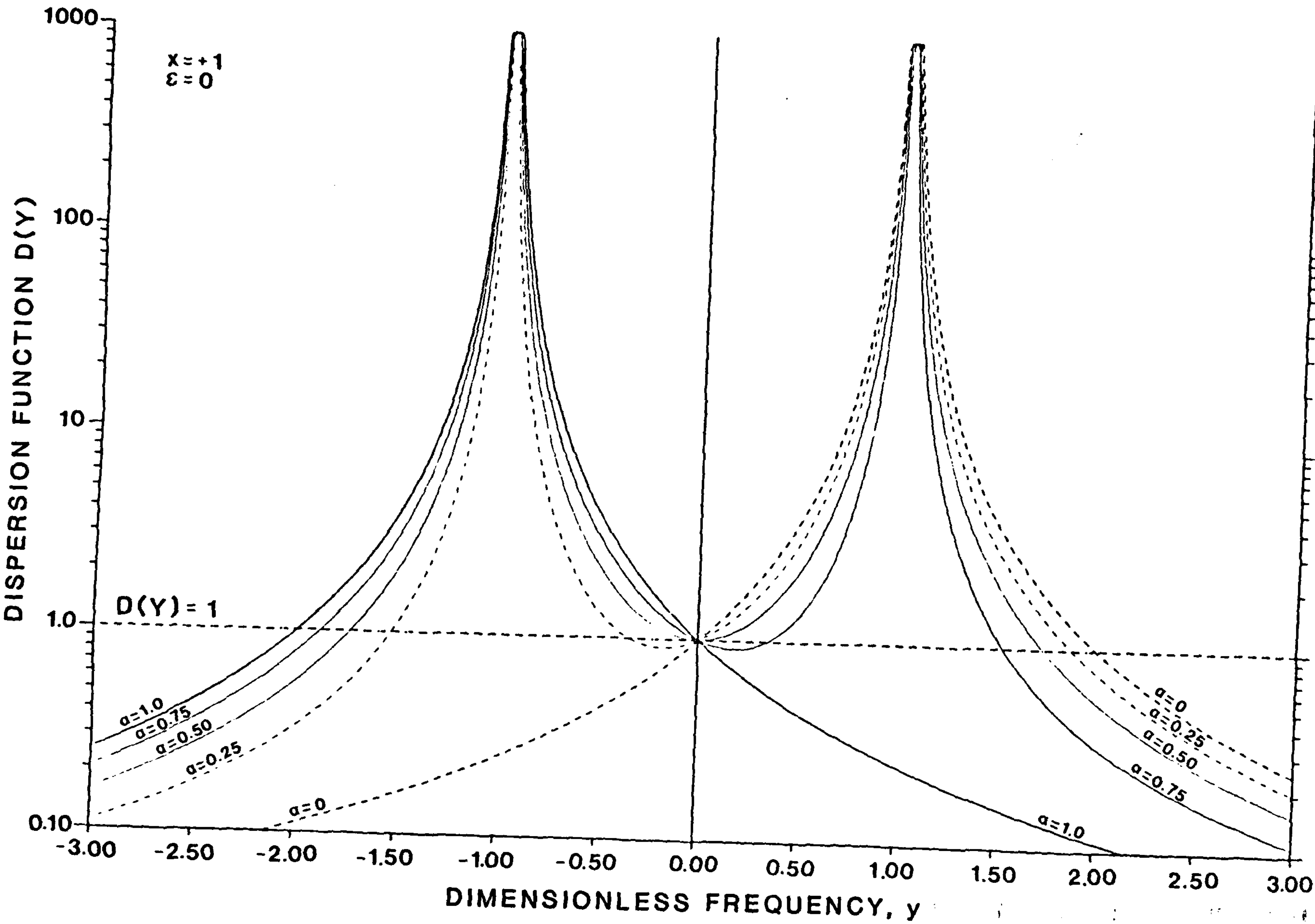
$$1 = \frac{\alpha}{(y-x)^2} + \frac{(1-\alpha)}{(y+x)^2} + \frac{\epsilon}{y^2}$$

or

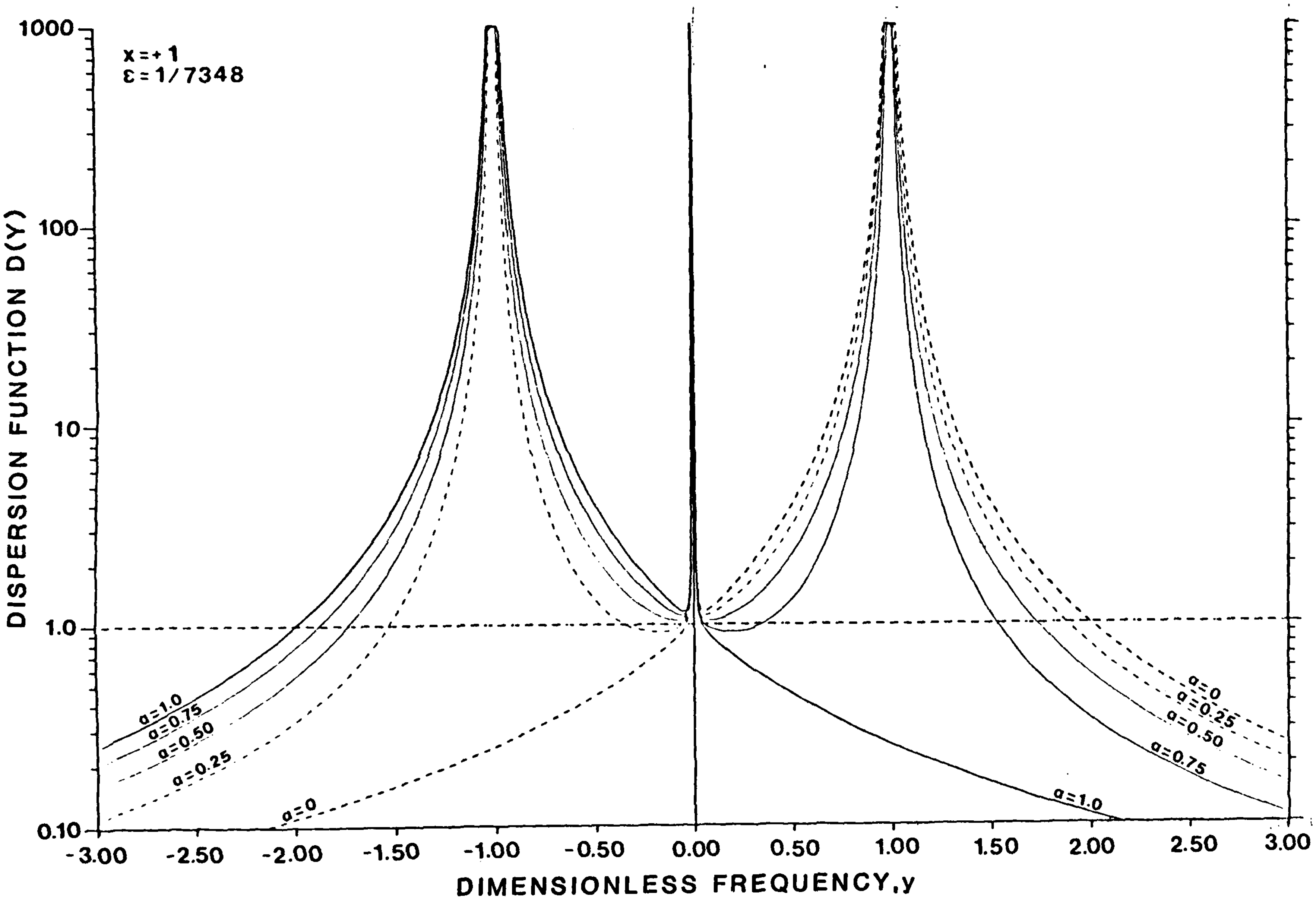
$$D(y) = 1 = \frac{y^2 + 2xy(2\alpha - 1) + x^2}{(y^2 - x^2)^2} + \frac{\epsilon}{y^2}$$

- This leads to a hexic dispersion equation,

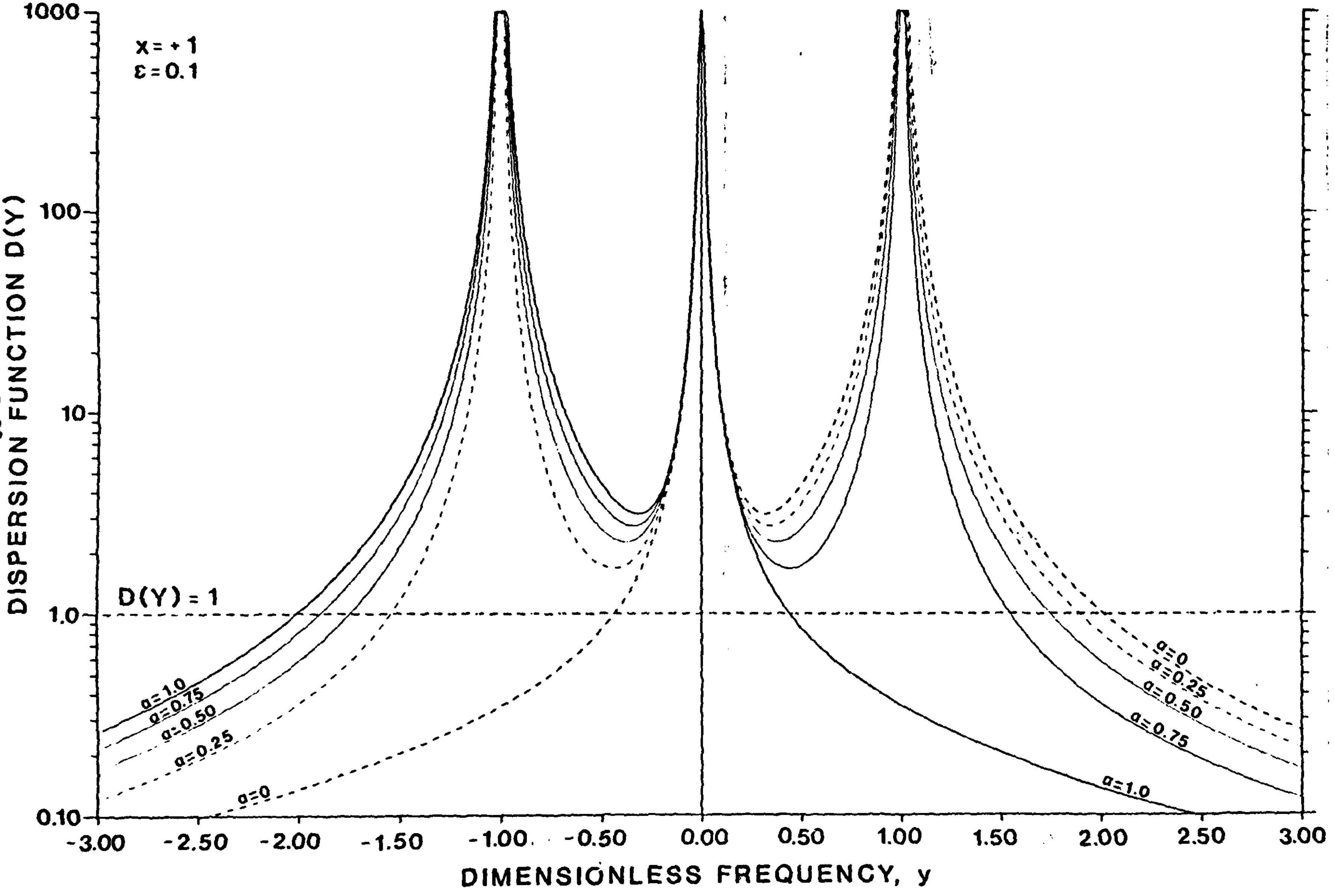
$$y^6 - (2x^2 + 1 + \epsilon)y^4 + 2x(1 - 2\alpha)y^3 + x^2(x^2 - 1 + 2\epsilon)y^2 - \epsilon x^4 = 0$$



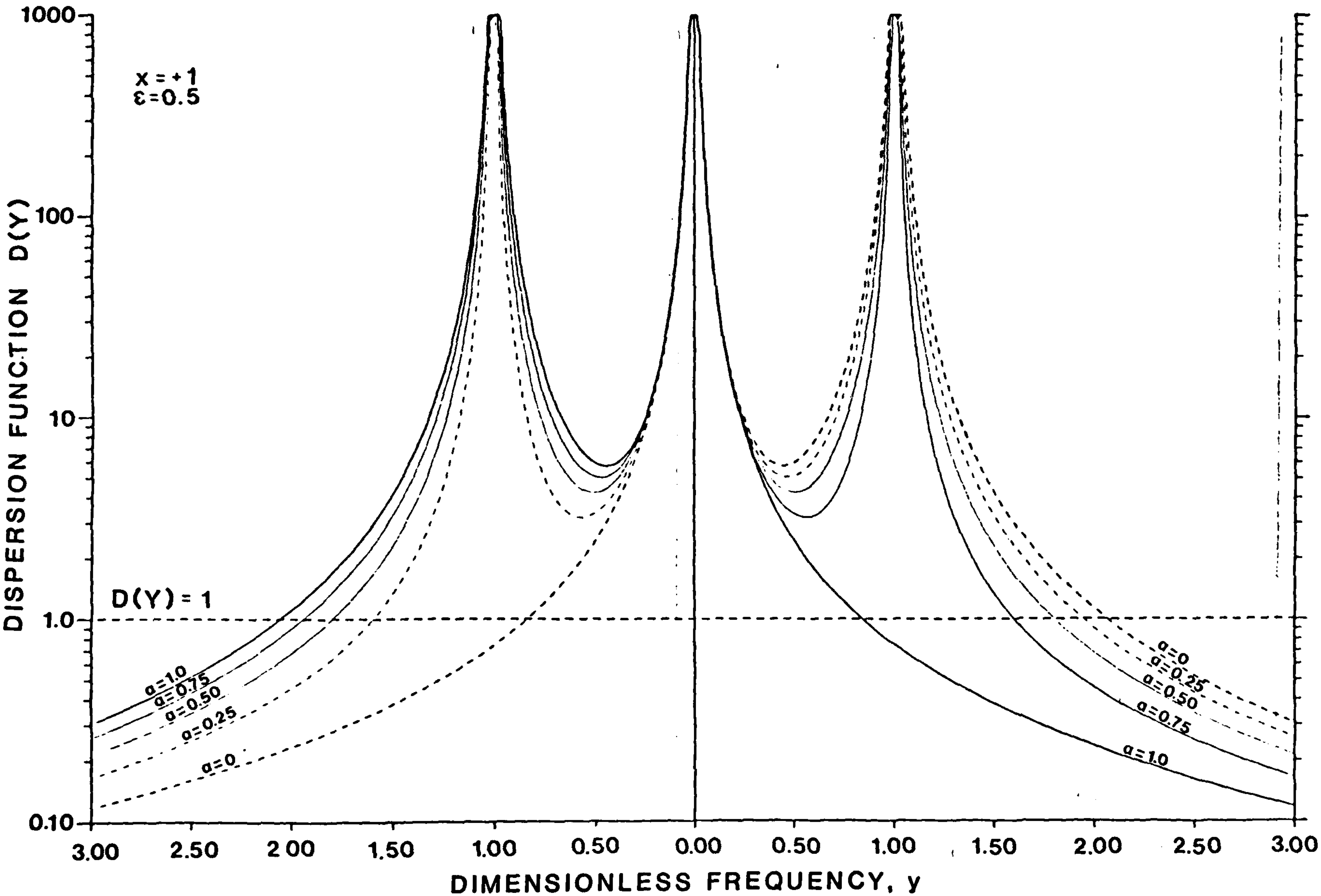
x = +1
ε = 0
D(Y) = 1
α=1.0
α=0.75
α=0.50
α=0.25
α=0
α=0
α=0.25
α=0.50
α=0.75
α=1.0
1000
100
10
1.0
0.10
DISPERSION FUNCTION D(Y)
-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
DIMENSIONLESS FREQUENCY, y



x = +1
ε = 1/7348
DISPERSION FUNCTION D(Y)
1000
100
10
1.0
0.10
-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
DIMENSIONLESS FREQUENCY, y
α=1.0
α=0.75
α=0.50
α=0.25
α=0
α=0
α=0.25
α=0.50
α=0.75
α=1.0



x = + 1
ε = 0.1
D(Y) = 1
α=1.0
α=0.75
α=0.50
α=0.25
α=0
α=0
α=0.25
α=0.50
α=0.75
α=1.0
1000
100
10
1.0
0.10
-3.00 -2.50 -2.00 -1.50 -1.00 -0.50 0.00 0.50 1.00 1.50 2.00 2.50 3.00
DISPERSION FUNCTION D(Y)
DIMENSIONLESS FREQUENCY, y



x = +1
ε = 0.5
D(Y) = 1
α=1.0
α=0.75
α=0.50
α=0.25
α=0
DISPERSION FUNCTION D(Y)
1000
100
10
1.0
0.10
3.00 2.50 2.00 1.50 1.00 0.50 0.00 0.50 1.00 1.50 2.00 2.50 3.00
DIMENSIONLESS FREQUENCY, y

THE QUASI - BUNEMAN LIMIT

MOST ELECTRONS FROM THE RIGHT, $0 \leq \alpha \leq \frac{1}{3}$

$\epsilon \ll 1, \quad \eta \ll 1$

- Consider the Buneman-like limit

$$0 \leq \alpha < \frac{1}{2}; \quad \epsilon \ll 1; \quad y \ll 1$$

Resonant activity at

$$x^2 \approx 1 - 2\epsilon$$

- Since $y \ll 1$, the y^6 and y^4 terms can be neglected, and the dispersion equation becomes

$$2(1-2\alpha)y^3 - \epsilon \; 0$$

or

$$y^3 = \frac{\epsilon}{2(1-2\alpha)}$$

- This has solutions

$$y_1 = \sqrt[3]{\frac{\epsilon}{2(1-2\alpha)}} \; ; \quad y_{2,3} = -\frac{1}{2}\sqrt[3]{\frac{\epsilon}{2(1-2\alpha)}} \mp \frac{i\sqrt{3}}{2}\sqrt[3]{\frac{\epsilon}{2(1-2\alpha)}}$$

- For the limit of no background plasma,

$$\epsilon \approx \frac{m_e}{m_i} \ll 1; \qquad \frac{n_{ce}}{n_b} \ll \frac{m_e}{m_i}; \qquad \omega_b \approx \omega_e$$

One obtains the classical Buneman result

$$\omega_{2,3} \approx \frac{\omega_i^{2/3}\,\omega_e^{1/3}}{2^{4/3}(1-2\alpha)^{1/3}}\left(-1 \pm i\sqrt{3}\right)$$

- For <u>some</u> background plasma, such that

$$n_{ce} \ll n_B \; , \quad \omega_B \approx \omega_e$$

$$\frac{m_e}{m_i} \ll \frac{n_{ce}}{n_B} \ll 1$$

We obtain an analog of the Buneman frequency,

$$\boxed{\omega_{2,3} \approx \frac{\omega_{ce}^{2/3}\,\omega_e^{1/3}}{2^{4/3}(1-2\alpha)^{1/3}}\left(-1 \pm i\sqrt{3}\right)}$$

- Let us now investigate the case $\alpha = \frac{1}{2}, \ \epsilon \ll 1.$

  The original hexic for this case becomes

$$y^6 - (2x^2 + \epsilon + 1)y^4 + x^2(x^2 + 2\epsilon - 1)y^2 - \epsilon x^4 = 0$$

From computer solutions, when $\epsilon \ll 1, y \ll 1,$ so higher powers of y can be neglected as an approximation. Neglecting y^6, y^4,

$$y^2 \approx \frac{\epsilon x^2}{x^2 + 2\epsilon - 1}$$

so the "action" occurs around $x^2 \approx 1-2\epsilon$, where y is no longer small and the y^4 term must be taken into account. For $x^2 \approx 1$, $\epsilon \ll 1$, neglecting y^6

$$-(3-3\epsilon)y^4 - \epsilon(1-2\epsilon)^2 = 0$$

- The approximate dispersion relation is

$$y^4 \approx -\frac{\epsilon}{3}\frac{(1-2\epsilon)^2}{(1-\epsilon)}$$

THE SOLUTION TO WHICH IS

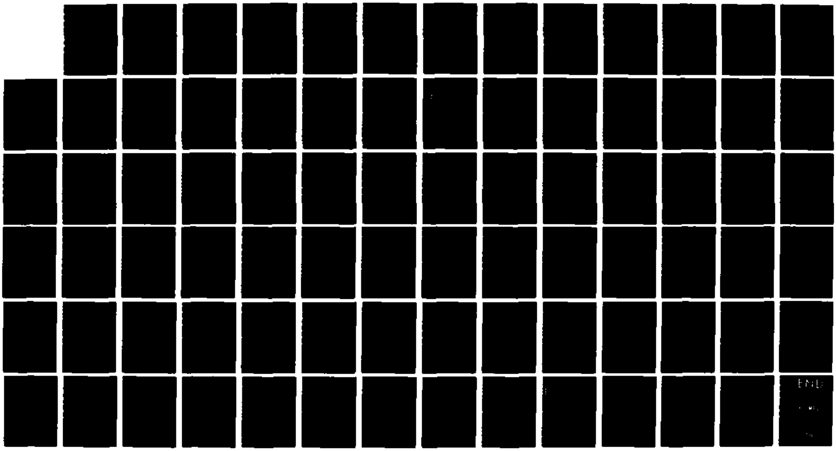
$$y \equiv \frac{\omega}{\omega_B} \approx \frac{(\pm 1 \pm i)}{\sqrt{2}} \sqrt[4]{\frac{\epsilon(1-2\epsilon)^2}{3(1-\epsilon)}}$$

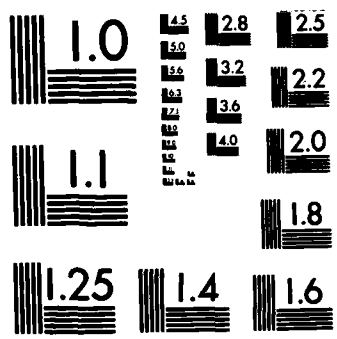
- If $\epsilon = 0$, only real or pure imaginary solutions to the hexic exist, and no propagating waves or radiation exist. This is aphysical, since the inter-penetrating beams cannot be quasi-neutral in the interaction region, with $\vec{\mathcal{E}} = 0$, as assumed by cold plasma theory.
- If

$$\epsilon \neq 0, \quad \epsilon = \frac{n_e}{n_i} > \frac{n_{ce}}{n_B}; \quad \epsilon \ll 1$$

AD-A160 425 ANNUAL PROGRESS REPORT ON CONTRACT AFOSR-81-0093 MARCH 15 1984 TO MARCH 1 (U) TENNESSEE UNIV KNOXVILLE PLASMA SCIENCE LAB J R ROTH 30 APR 85 UTK-PSL-85-3 3/3

UNCLASSIFIED AFOSR-TR-85-0870 AFOSR-81-0093 F/G 20/9 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

no significant cold background plasma exists, and

$$\omega = \frac{\omega_b \epsilon^{\frac{1}{4}}}{\sqrt{2}\, 3^{1/4}} \sqrt[4]{\frac{(1-2\epsilon)^2}{(1-\epsilon)}} \, (\pm 1 \pm i)$$

Since

$$\epsilon^{\frac{1}{4}} \approx \sqrt{\frac{\omega_i}{\omega_b}} \approx \sqrt{\frac{\omega_i}{\omega_c}}$$

We recover the original geometric mean emission frequency,

$$W_{cm} = \frac{\sqrt{W_e W_i}}{\sqrt{2}\,\sqrt[4]{3}} \left(\frac{(1-2\epsilon)}{(1-\epsilon)} \right)^{1/4} \approx \frac{\sqrt{W_e W_i}}{\sqrt{2}\,\sqrt[4]{3}}$$

- If there is a significant amount of cold background plasma, but $\epsilon \ll 1$,

$$\frac{m_e}{m_i} \ll \frac{n_{ce}}{n_0} \ll 1$$

and

$$\epsilon^{\frac{1}{4}} \approx \sqrt[4]{\frac{n_{ce}}{n_0}} = \sqrt{\frac{\omega_{ce}}{\omega_0}}$$

- and we obtain a new geometric mean frequency,

$$\boxed{\omega = \frac{\sqrt{\omega_{ce}\,\omega_b}}{\sqrt{2}\,\sqrt[4]{3}}\,\sqrt[4]{\frac{(1-2\epsilon)^2}{(1-\epsilon)}}\,(\pm 1 \pm i)}$$

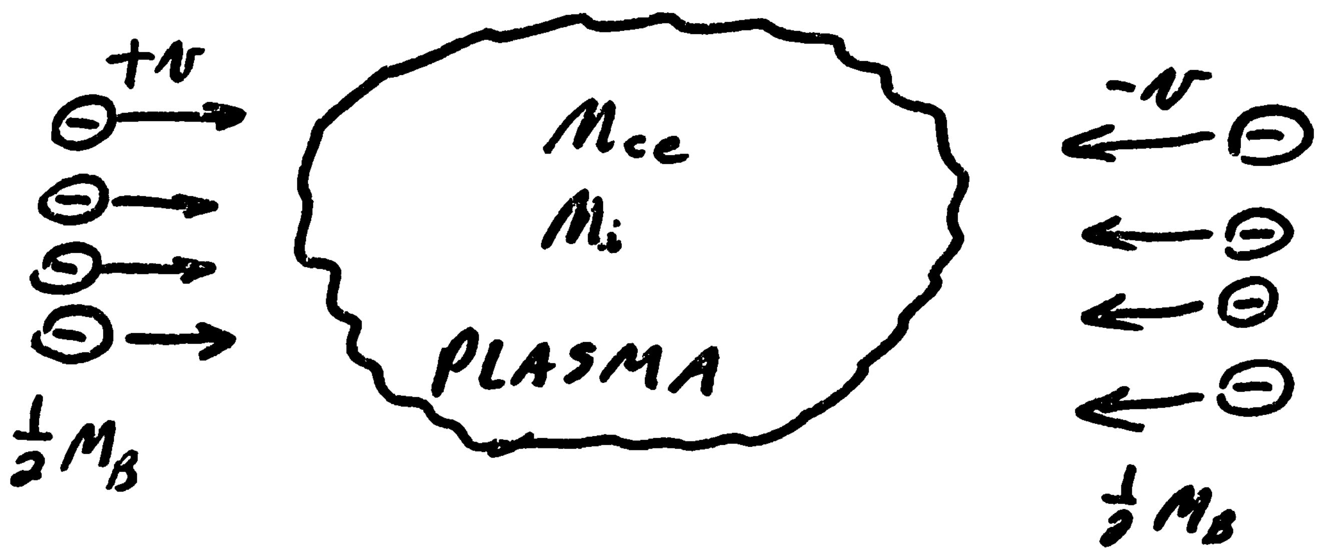
$$\omega \overset{\epsilon \ll 1}{\approx} \frac{\sqrt{\omega_{ce}\,\omega_b}}{\sqrt{2}\,\sqrt[4]{3}}$$

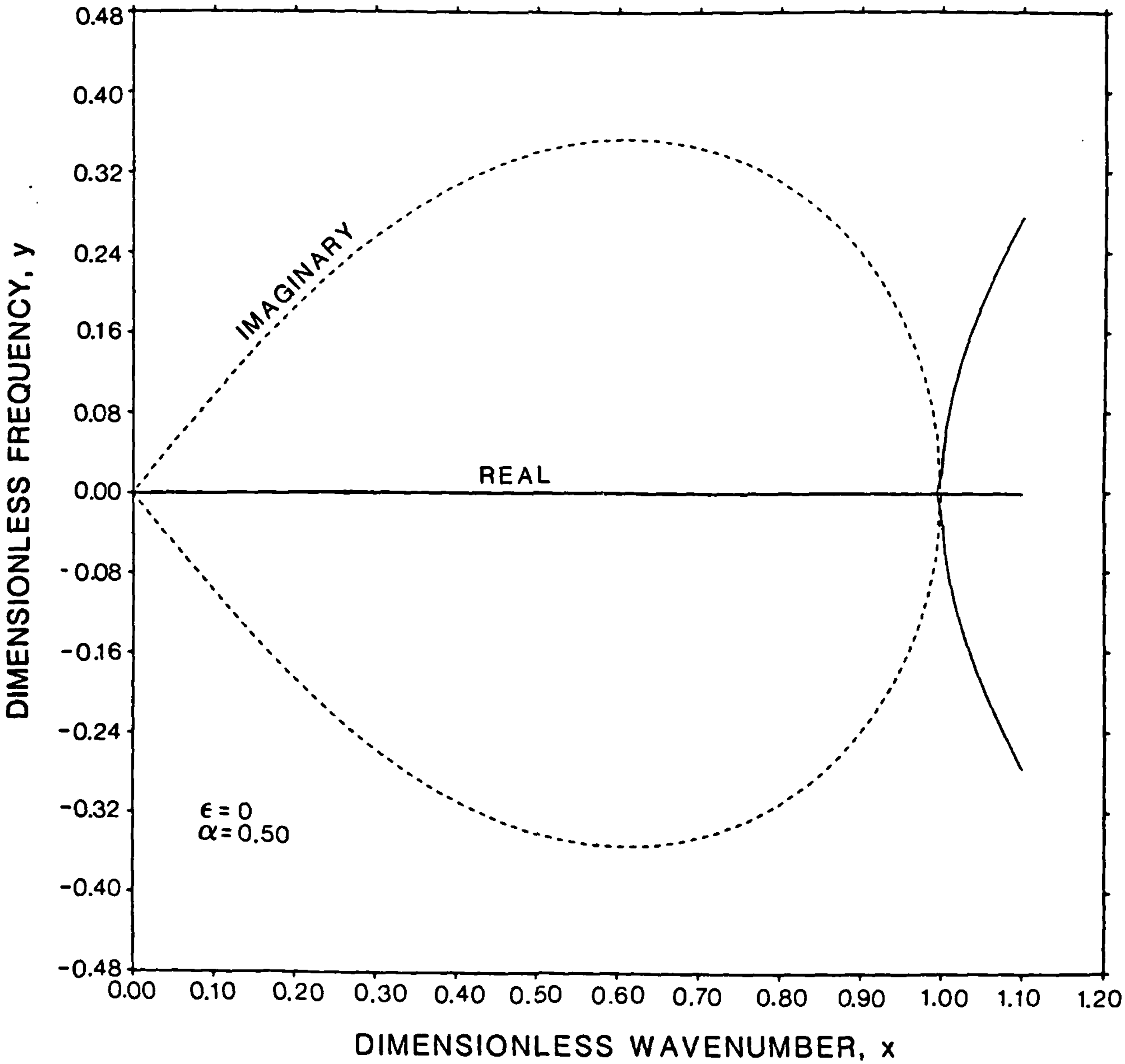
So we obtain a new geometric mean frequency at the geometric mean of the beam and cold electron plasma frequencies.

STRONG BEAM CASE

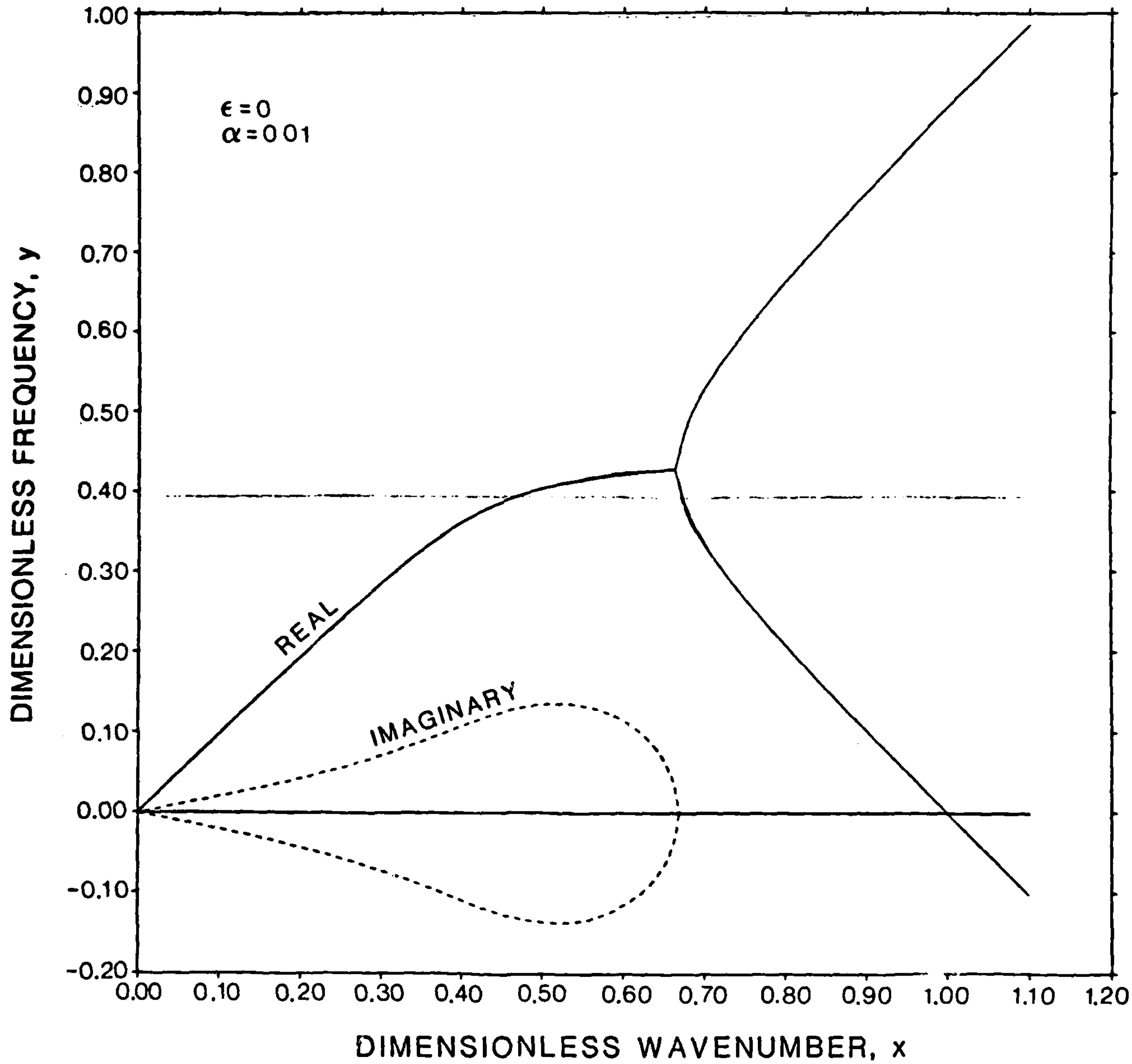
EQUAL AND OPPOSITE ELECTRON BEAMS

$$\alpha = \frac{1}{2}, \quad \epsilon \ll 1$$

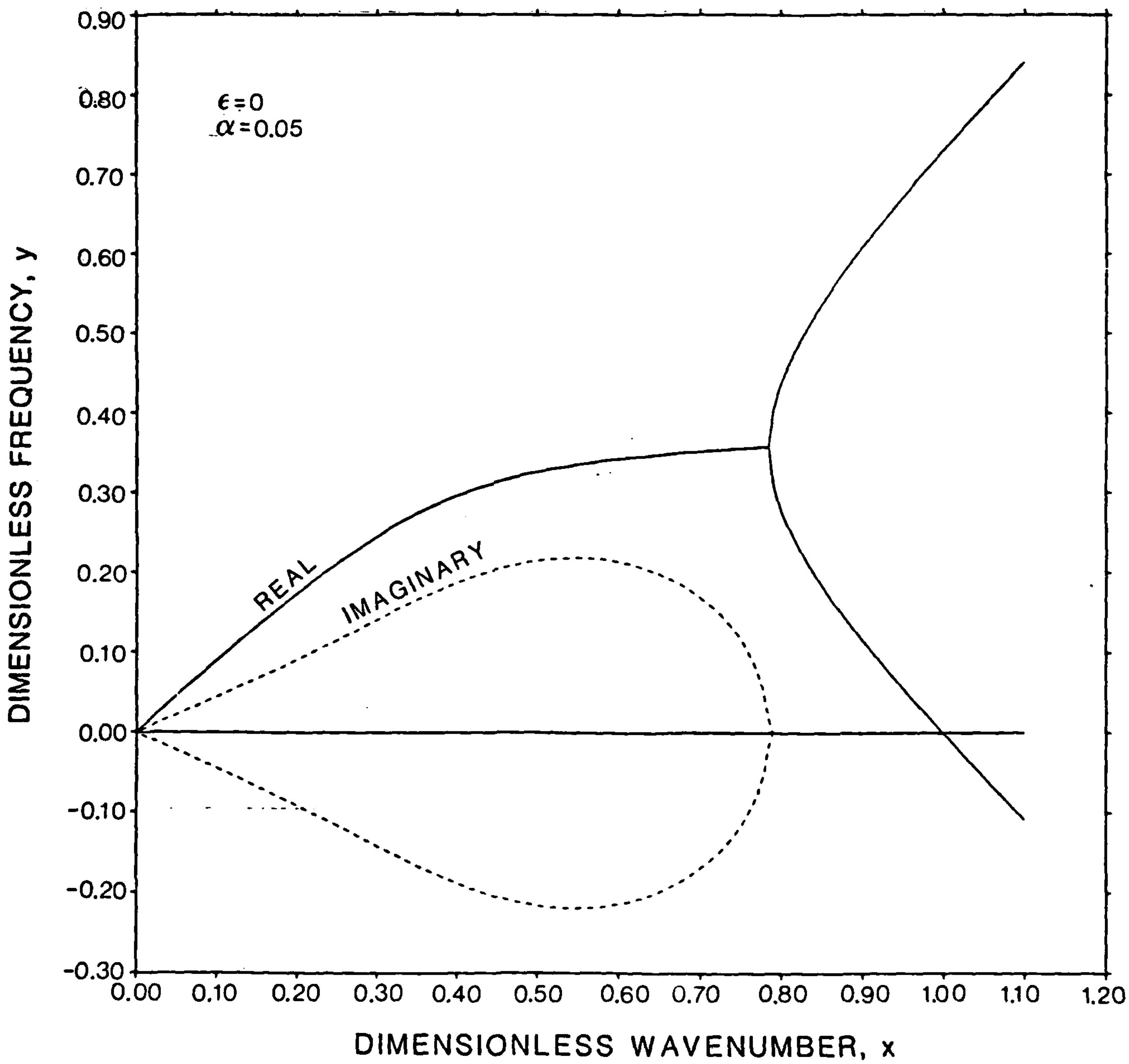




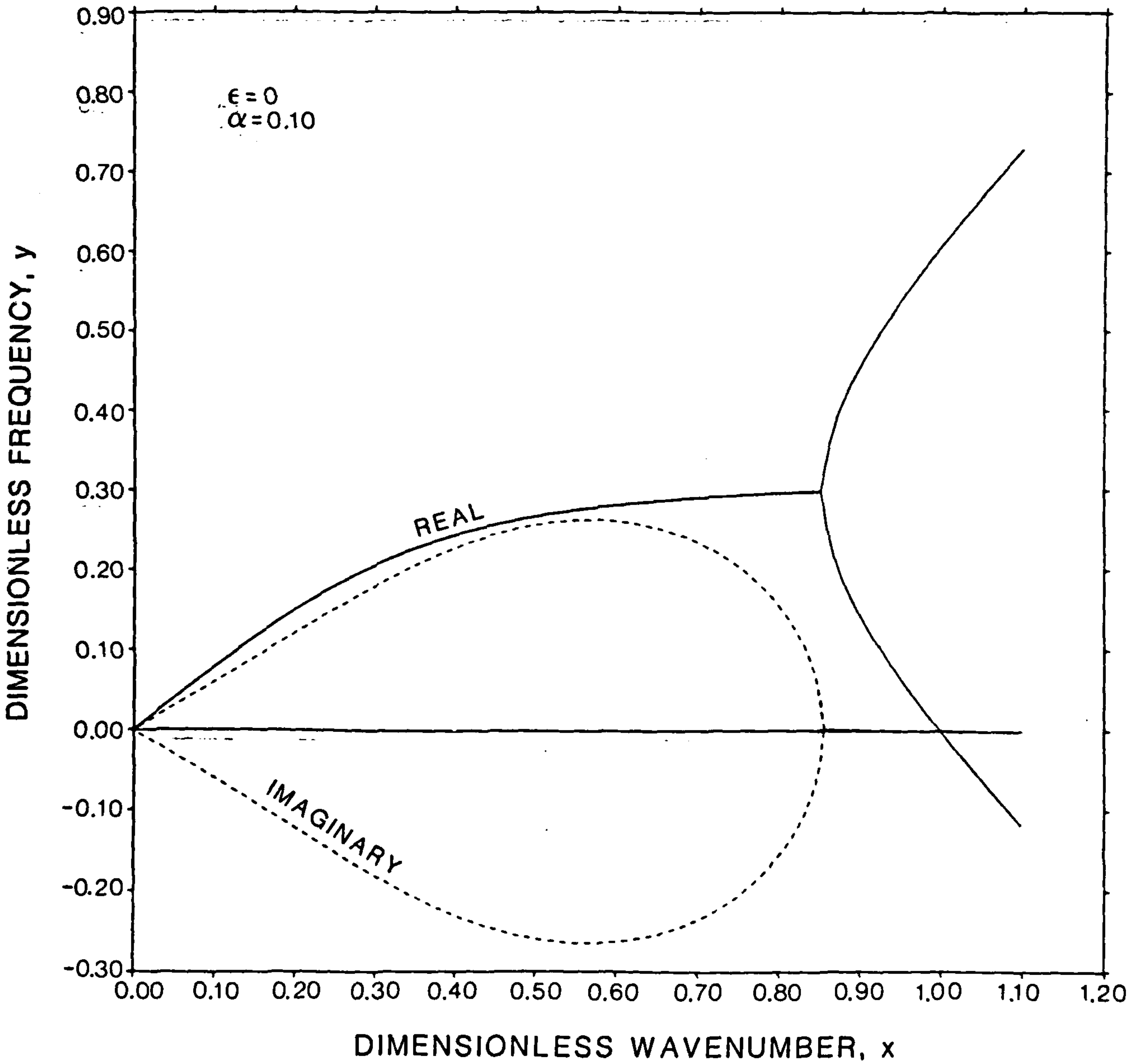
DIMENSIONLESS FREQUENCY, y
0.48
0.40
0.32
0.24
0.16
0.08
0.00
-0.08
-0.16
-0.24
-0.32
-0.40
-0.48
IMAGINARY
REAL
ϵ = 0
α = 0.50
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
DIMENSIONLESS WAVENUMBER, x



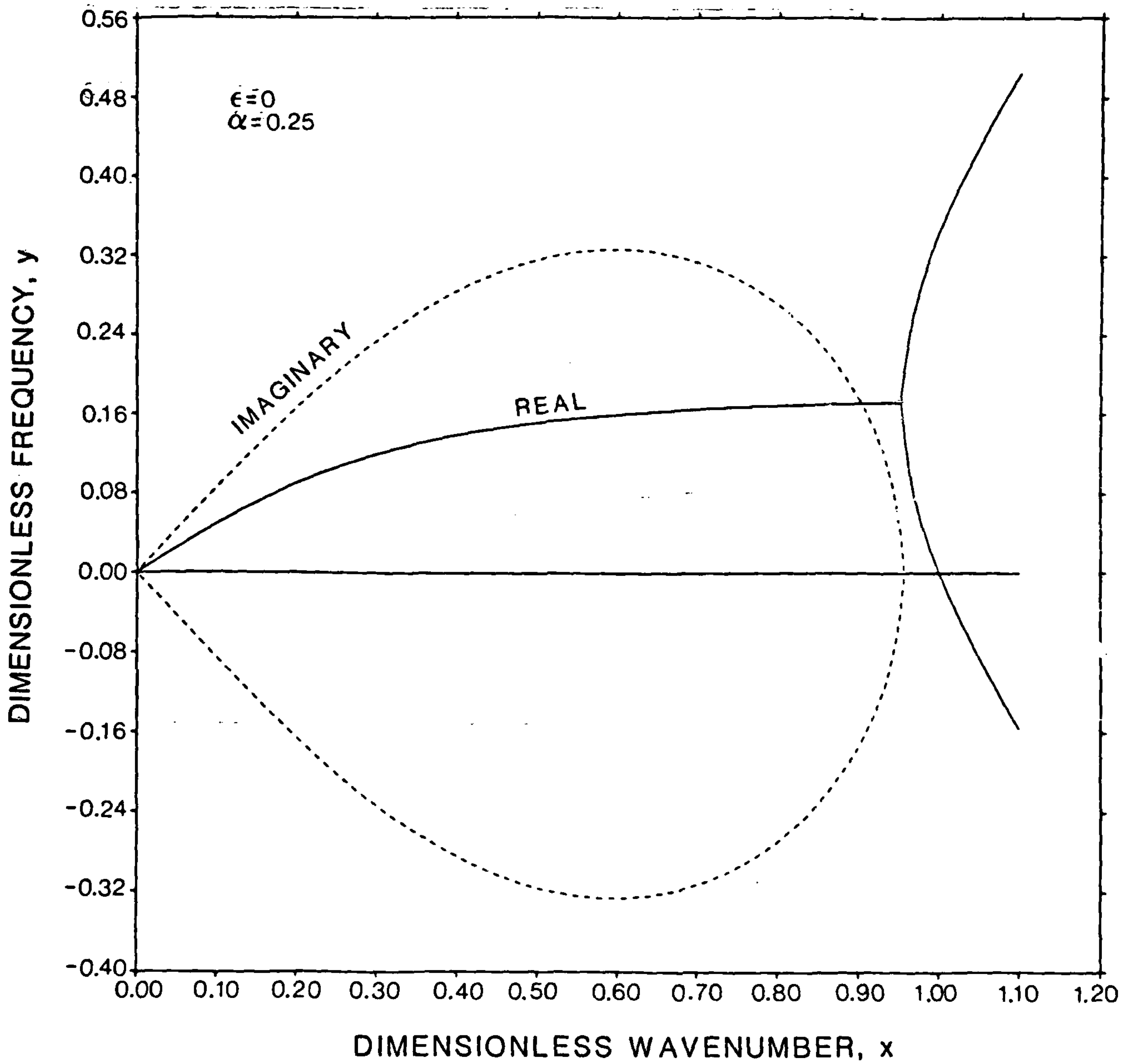
ϵ = 0
α = 0.01
REAL
IMAGINARY
DIMENSIONLESS FREQUENCY, y
DIMENSIONLESS WAVENUMBER, x
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20



0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20
$\epsilon=0$
$\alpha=0.05$
REAL
IMAGINARY
DIMENSIONLESS FREQUENCY, y
DIMENSIONLESS WAVENUMBER, x



ϵ = 0
α = 0.10
REAL
IMAGINARY
DIMENSIONLESS FREQUENCY, y
DIMENSIONLESS WAVENUMBER, x
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20



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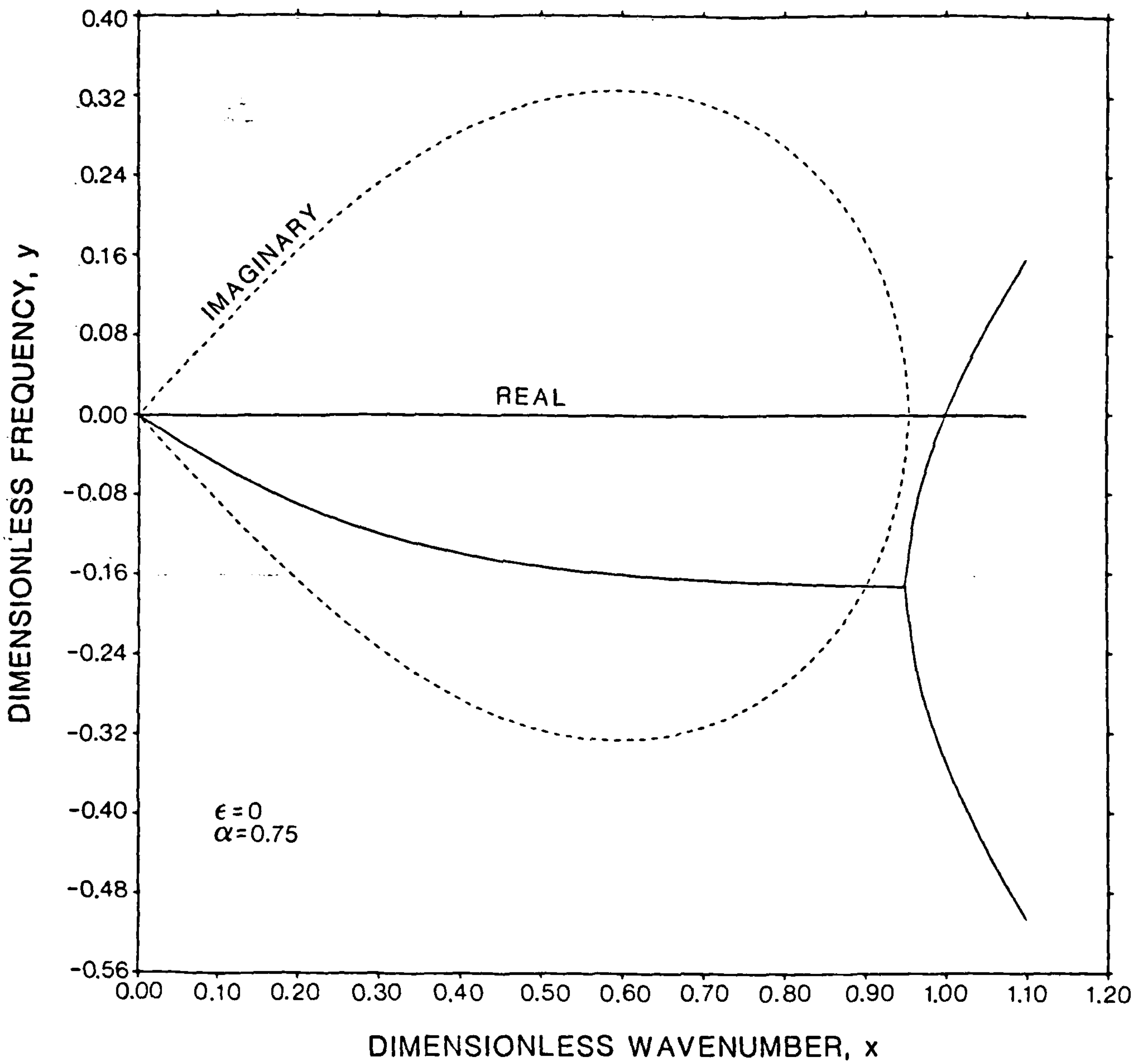
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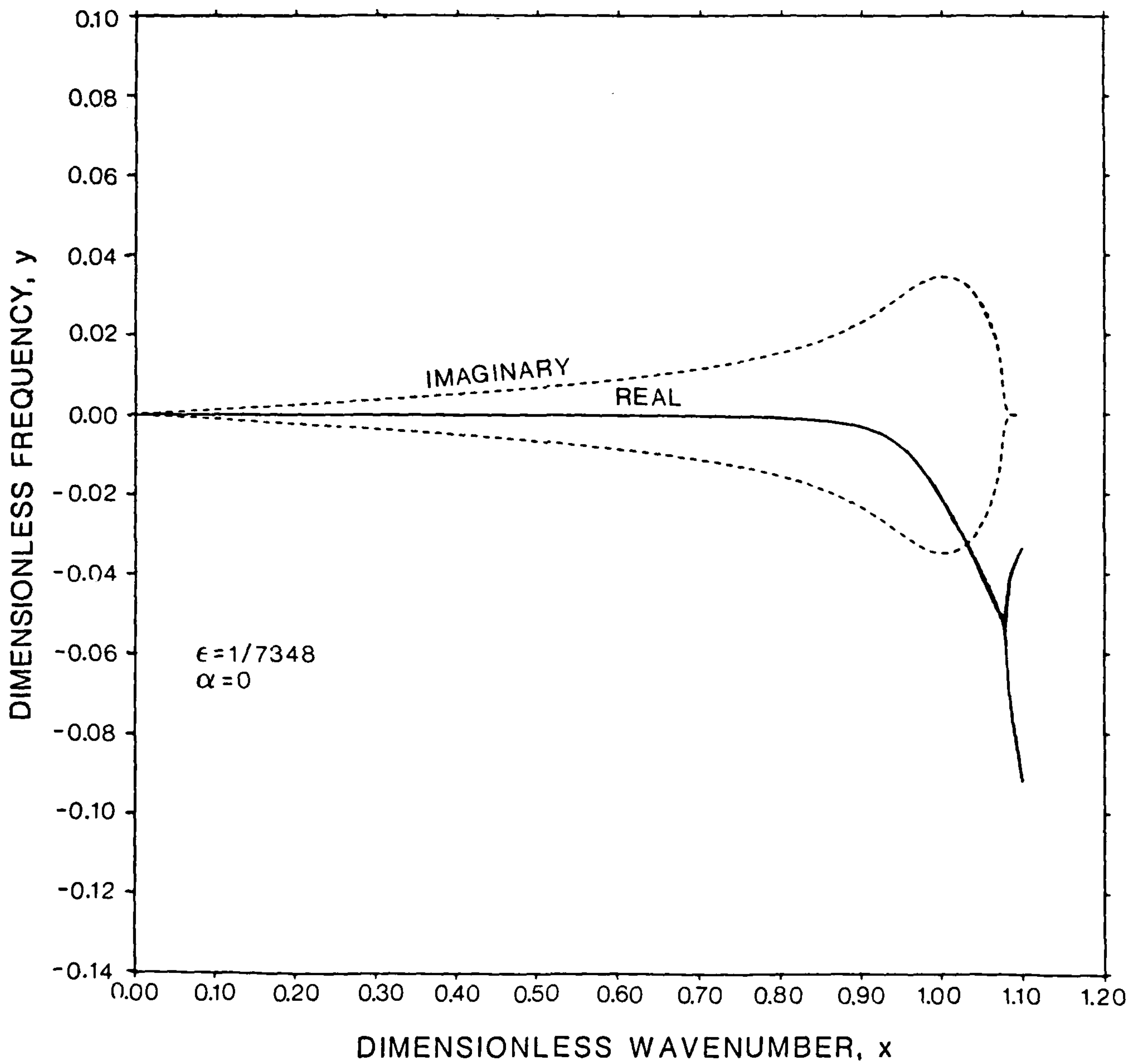

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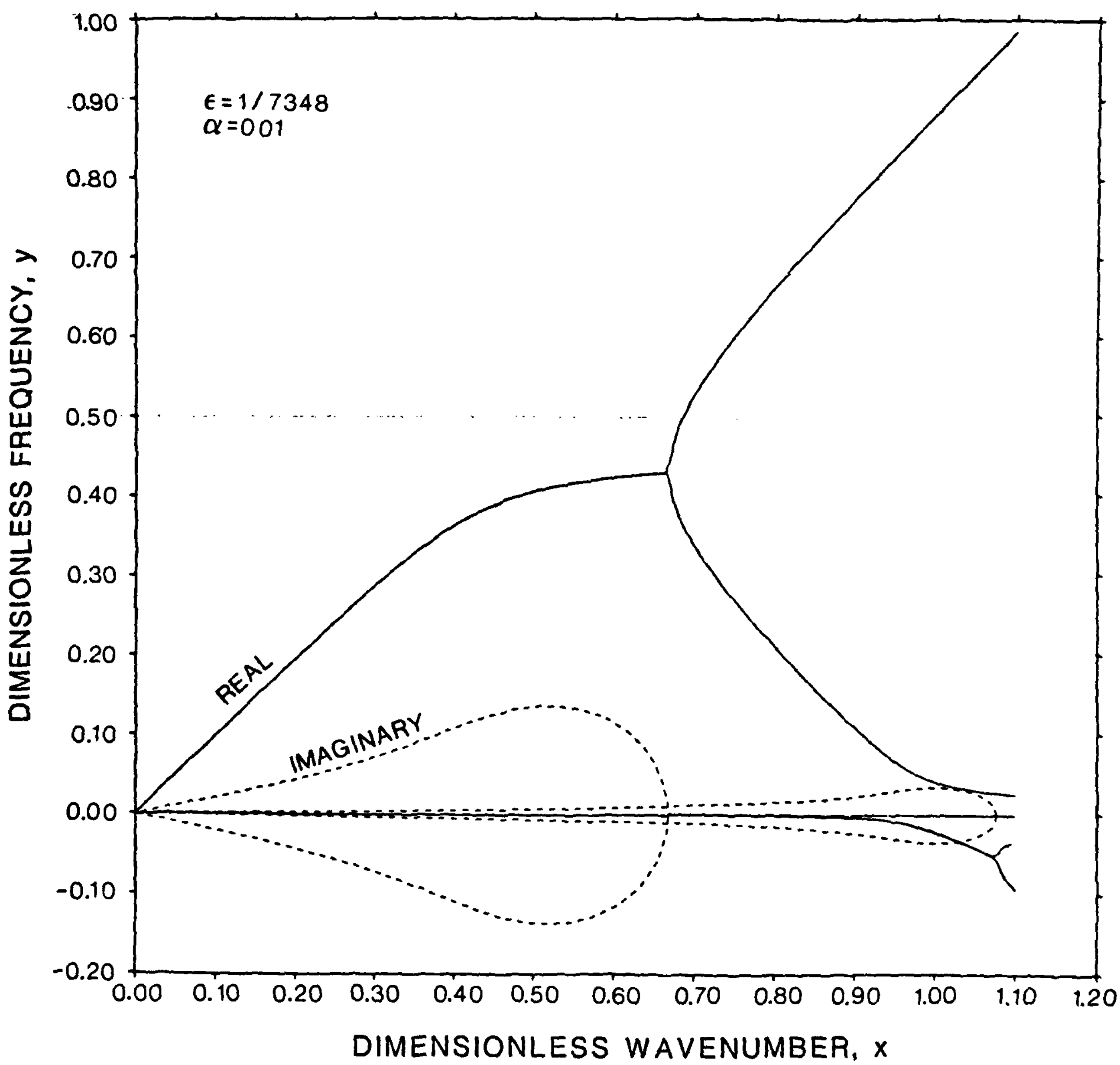

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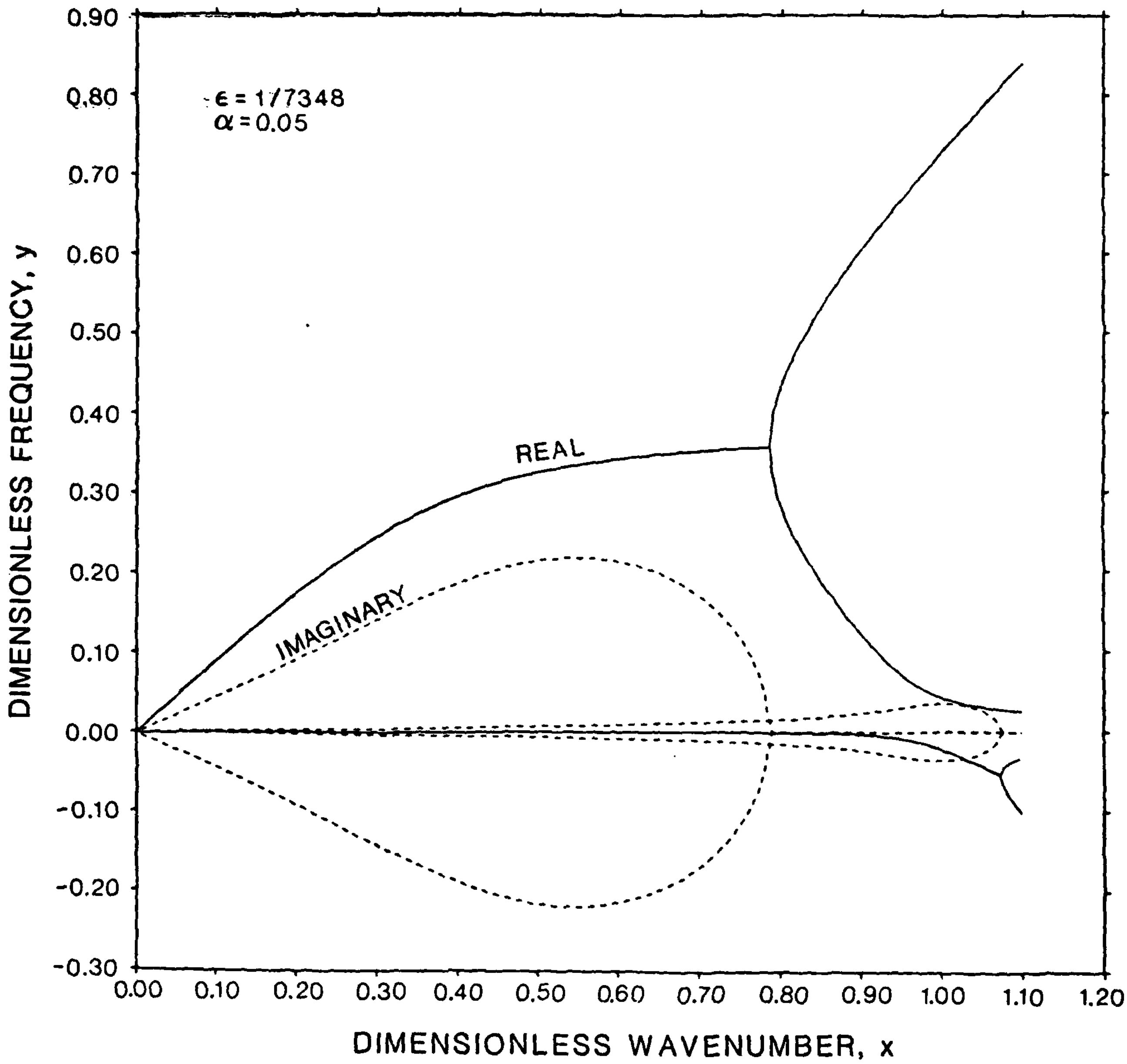
DIMENSIONLESS WAVENUMBER, x



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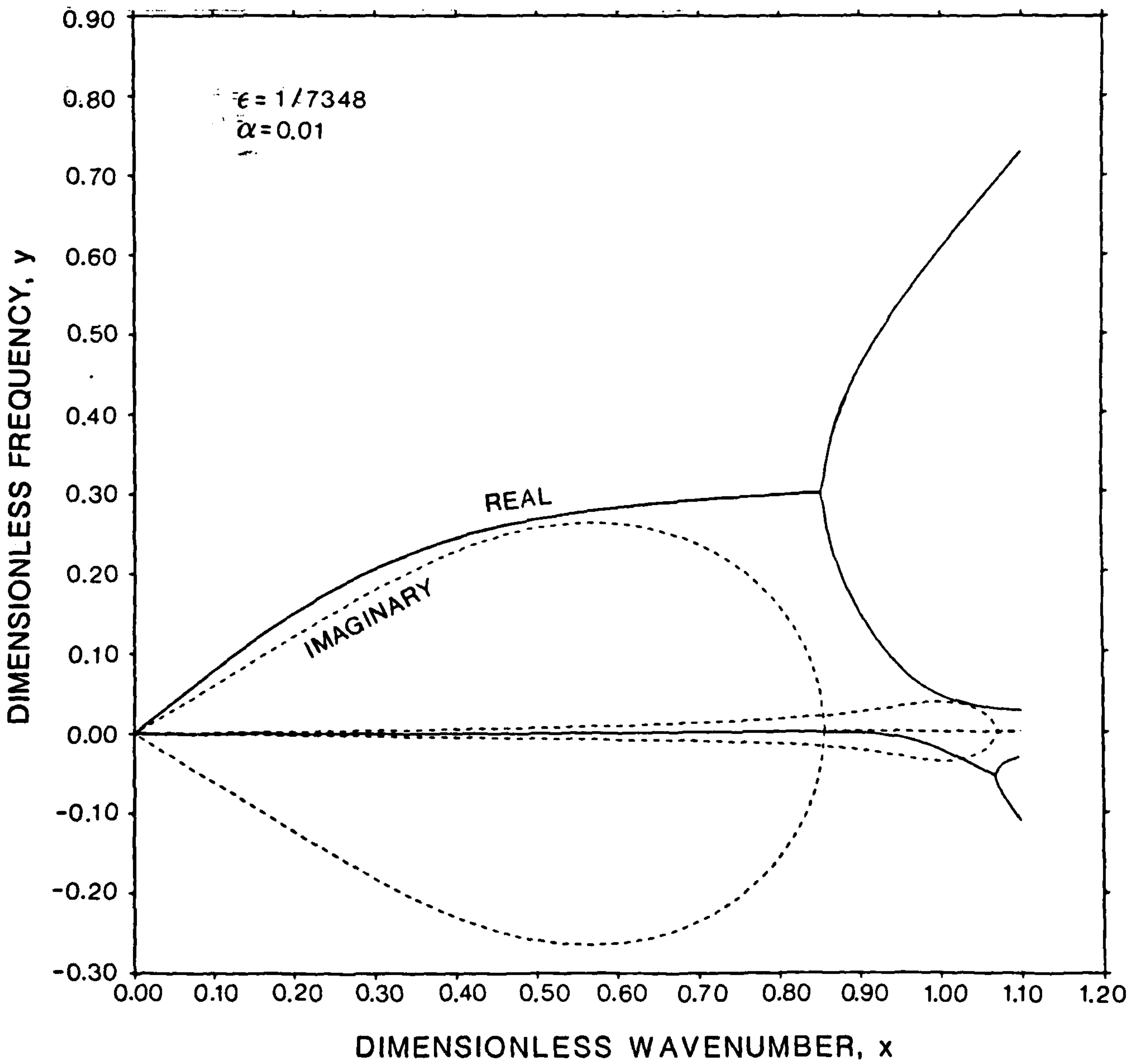
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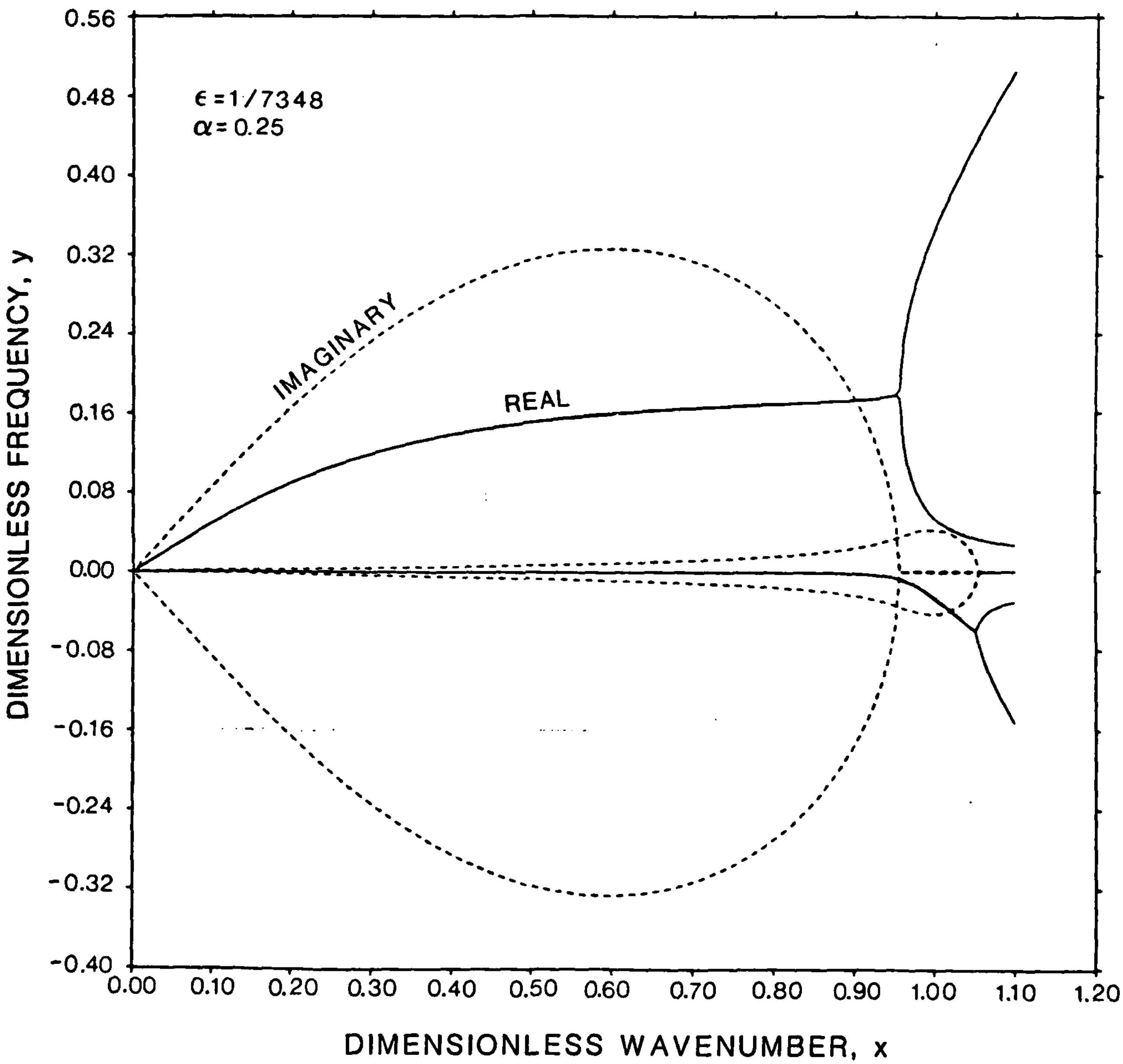
DIMENSIONLESS WAVENUMBER, x



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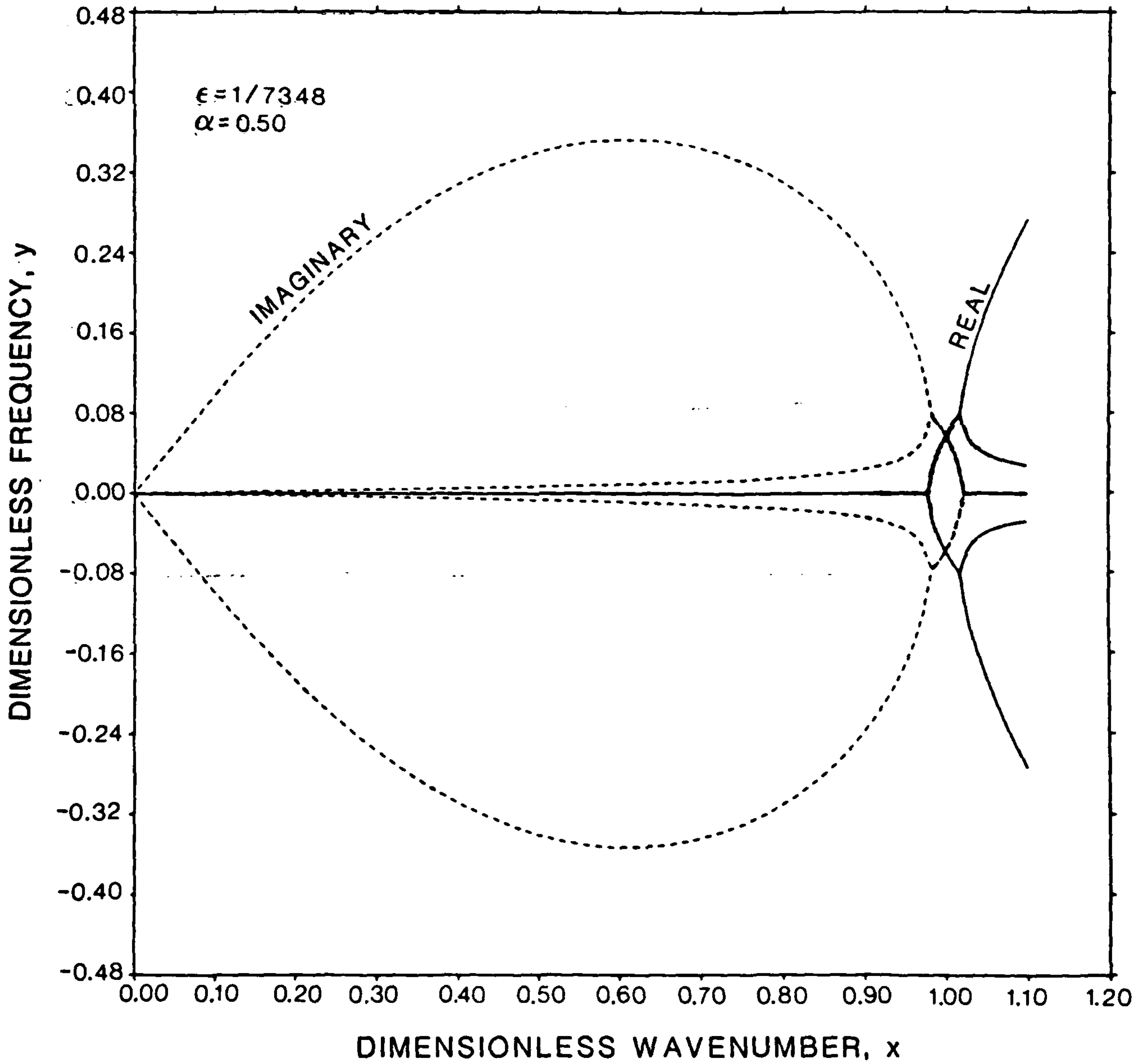

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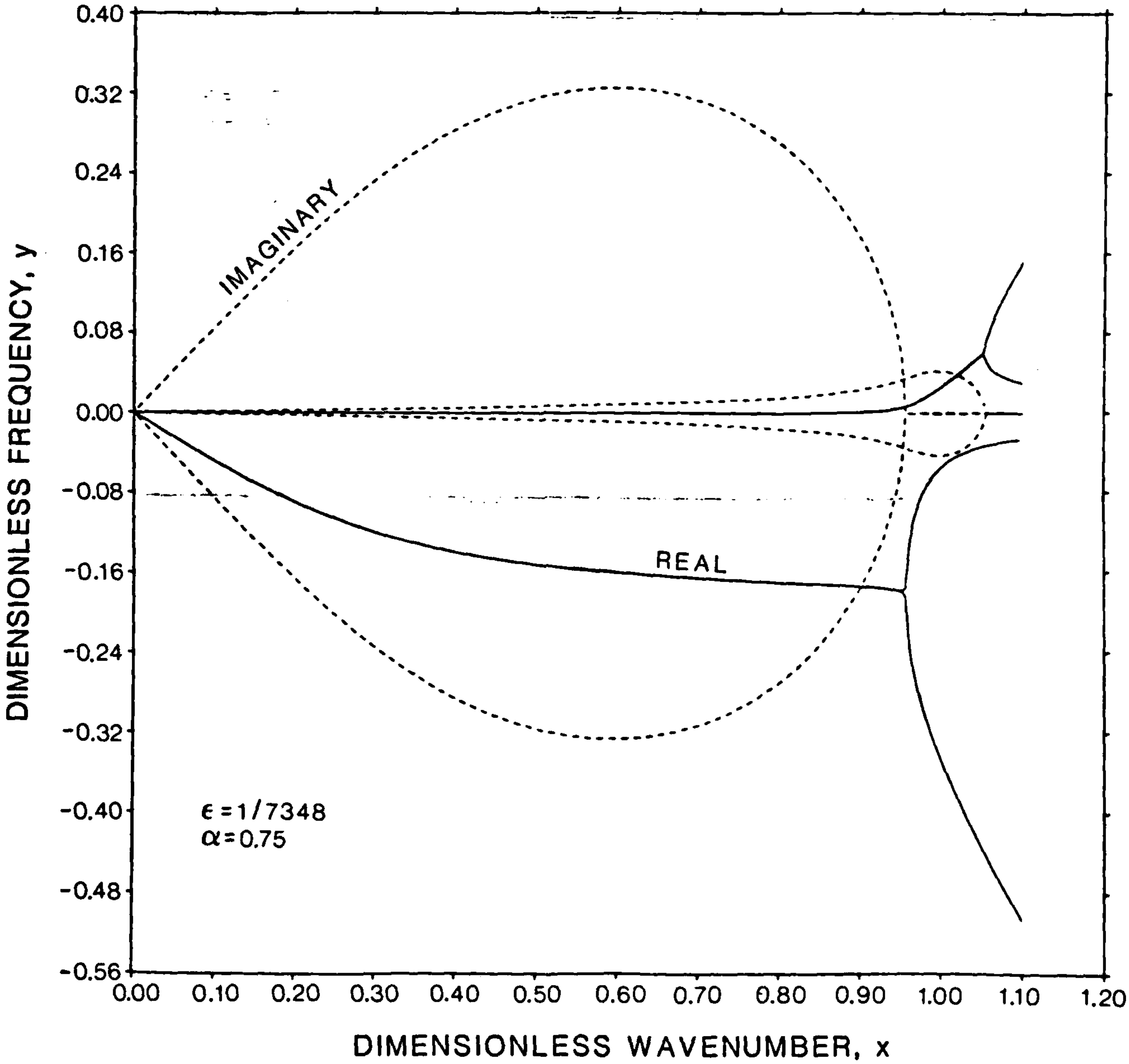

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DIMENSIONLESS FREQUENCY, y
IMAGINARY
REAL
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α=0.75
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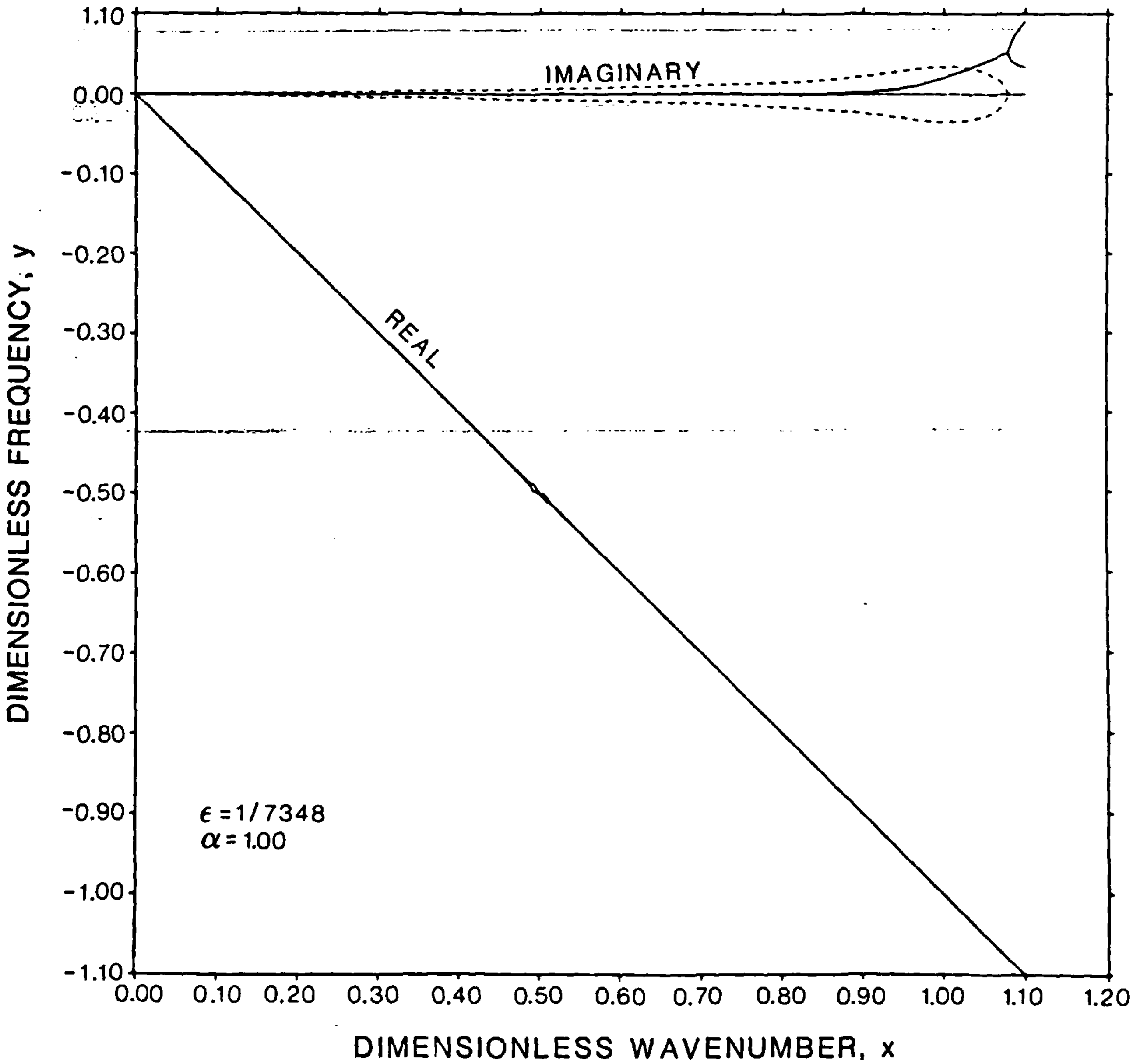
1.00
1.10
1.20
DIMENSIONLESS WAVENUMBER, x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α = 1.00
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DIMENSIONLESS WAVENUMBER, x
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-0.90
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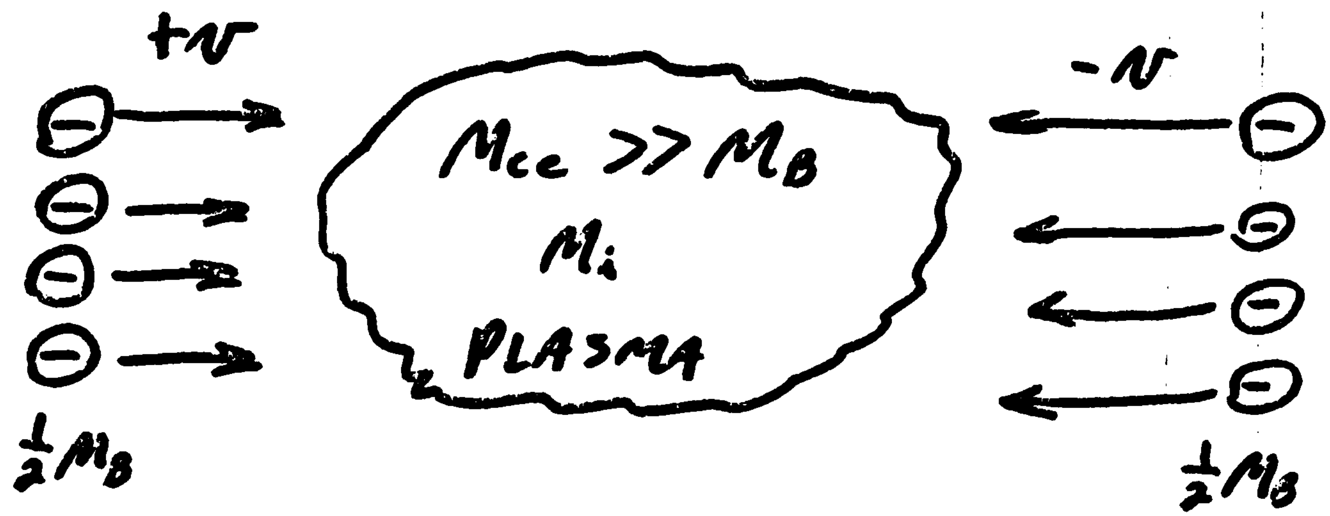
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20

WEAK, EQUAL INTERPENETRATING BEAM CASE

$$\alpha = \frac{1}{2}, \quad \epsilon >> 1, \quad M_{ce} >> M_B$$



- Let us now look at a third case which can be treated analytically:

1.) $\alpha = \frac{1}{2}$

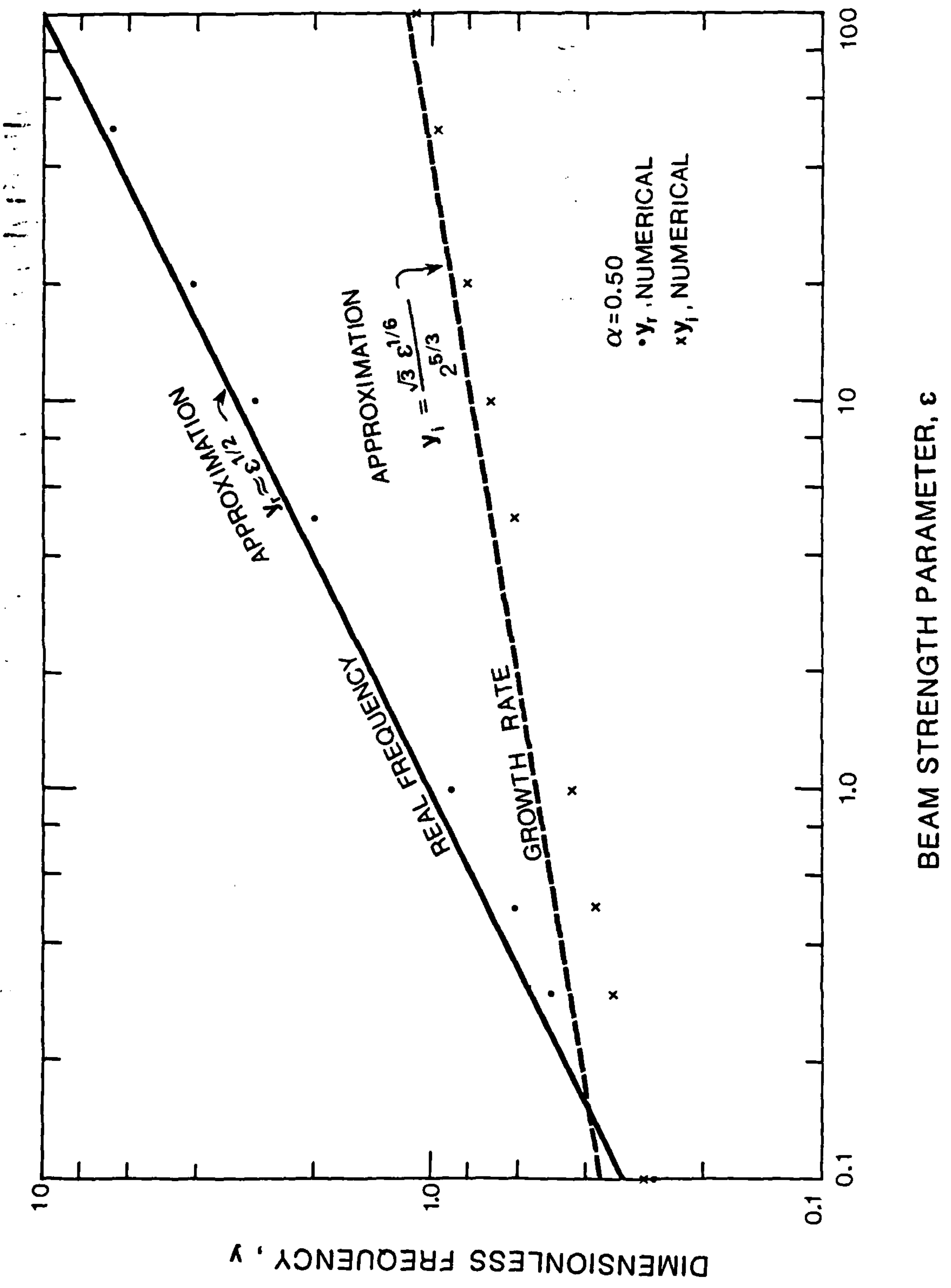
2.) $\epsilon >> 1, \quad M_{ce} >> M_B$

- From numerical solution of dispersion hexic, one finds graphically for $\epsilon >>$ 1 (weak beam case)

$$x_{max} \approx \frac{1}{2} + \epsilon^{\frac{1}{2}}$$

For large ϵ,

$$\underline{x_{max} \rightarrow \epsilon^{1/2}}$$



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BEAM STRENGTH PARAMETER, ε
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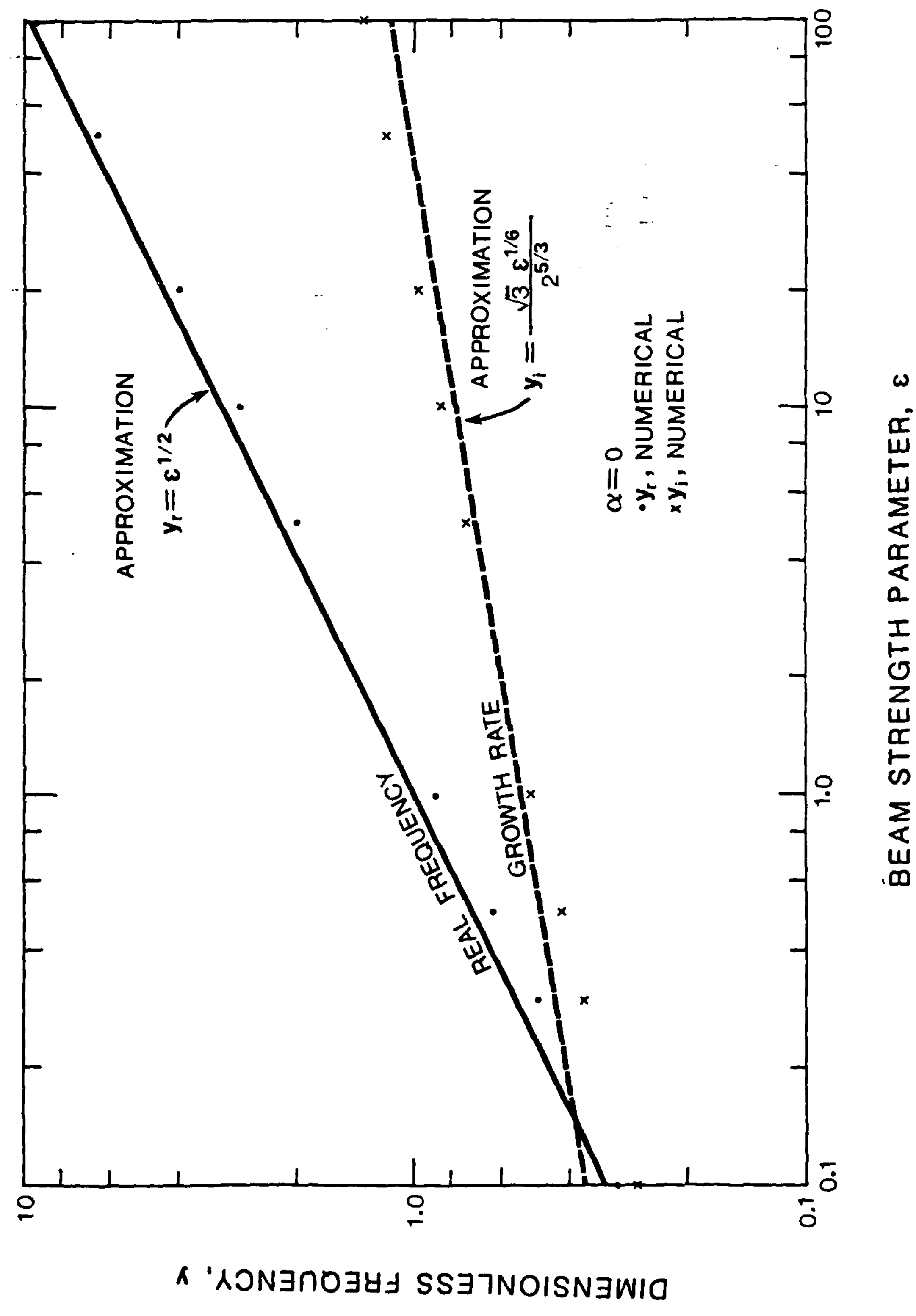
0.1
100
REAL FREQUENCY
GROWTH RATE
APPROXIMATION
$y_r = \varepsilon^{1/2}$
APPROXIMATION
$y_i = \frac{\sqrt{3}\,\varepsilon^{1/6}}{2^{5/3}}$
$\alpha = 0.50$
•y_r, NUMERICAL
×y_i, NUMERICAL



DIMENSIONLESS FREQUENCY, y
BEAM STRENGTH PARAMETER, ε
10
1.0
0.1
0.1
1.0
10
100
APPROXIMATION
$y_r = \varepsilon^{1/2}$
APPROXIMATION
$y_i = \frac{\sqrt{3}\,\varepsilon^{1/6}}{2^{5/3}}$
REAL FREQUENCY
GROWTH RATE
α = 0
• y_r, NUMERICAL
× y_i, NUMERICAL

- For the above limit, the basic hexic dispersion equation

$$y^6 - (1 + \epsilon + 2x^2)y^4 + 2x(1 - 2\alpha)y^3$$
$$+ x^2(2\epsilon + x^2 - 1)y^2 - \epsilon x^4 = 0$$

Becomes, for

$$\epsilon >> 1, \quad x \approx x_{max} \approx \epsilon^{1/2}$$

$$y^6 - (1 + 3\epsilon)y^4 + 2\epsilon^{1/2}(1 - 2\alpha)y^3 + \epsilon(3\epsilon - 1)y^2 - \epsilon^3 = 0$$

- Now, if equal and opposite beams, $\alpha = \frac{1}{2}$; <u>or</u>, anticipating a result,

$y \sim \epsilon^{1/2}$, so the y^3 term is smaller than the others by a factor of ϵ.

We therefore ignore it,

$$y^6 - (3\epsilon + 1)y^4 - \epsilon(1 - 3\epsilon)y^2 - \epsilon^3 = 0$$

- This can be reduced to a cubic in y^2 of the standard form

$$y^6 + p\,y^4 + q\,y^2 + r = 0$$

where

$$p = -(3\epsilon + 1)\,; \quad q = -\epsilon(1 - 3\epsilon); \quad r = -\epsilon^3$$

- We reduce this to the normal form for solution of a cubic equation,

$$X^3 + aX + b = 0$$

With the transformation

$$y^2 = X - \frac{p}{3} = X + \epsilon + \frac{1}{3}$$

- Substituting, we find

$$a = \frac{1}{3}(3q - p^2) = \frac{-(9\epsilon + 1)}{3}$$

$$b = \frac{1}{27}[2p^3 - 9pq + 27r]$$

$$b = -\left(2\epsilon^2 + \epsilon + \frac{2}{27}\right)$$

- The cubic solution requires that the discriminant be calculated,

$$D \equiv \frac{b^2}{4} + \frac{a^3}{27} = \epsilon^4 - \frac{5\epsilon^2}{4 \times 27}$$

- The discriminant is positive, implying one real and two complex conjugate solutions. The solutions are

$$X_1 = A + B\ ;\ X_{2,3} = -\frac{1}{2}(A + B) \pm \frac{i\sqrt{3}}{2}(A - B)$$

where

$$A = \sqrt[3]{-\tfrac{1}{2}b + D^{1/2}} \quad ; \qquad B = \sqrt[3]{-\tfrac{1}{2}b - D^{1/2}}$$

neglecting all but the highest powers of ϵ,

$$A \approx 2^{\frac{1}{3}} \epsilon^{\frac{2}{3}} \quad ; \qquad B \approx \frac{\epsilon^{1/3}}{2^{1/3}}$$

- The solutions in X are

$$X_1 = A + B \approx 2^{\frac{1}{3}} \epsilon^{2/3}$$

and $$X_{2,3} \approx -\left(\frac{\epsilon}{2}\right)^{2/3} \pm i\,\frac{\sqrt{3}\,\epsilon^{2/3}}{2^{2/3}}$$

$$y_1^2 = X_1 + \epsilon + \frac{1}{3} \approx \epsilon$$

$$y_1 \approx \epsilon^{1/2}$$

$$y_{2,3}^2 \approx \epsilon \pm i\,\frac{\sqrt{3}\,\epsilon^{2/3}}{2^{2/3}}$$

- To solve the complex equation above,

$$y = y_r + i\,y_i$$

- The solutions are

$$y_r \sim \epsilon^{\frac{1}{2}}$$

$$y_i \sim \pm \frac{\sqrt{3}}{2^{5/3}} \epsilon^{1/6}$$

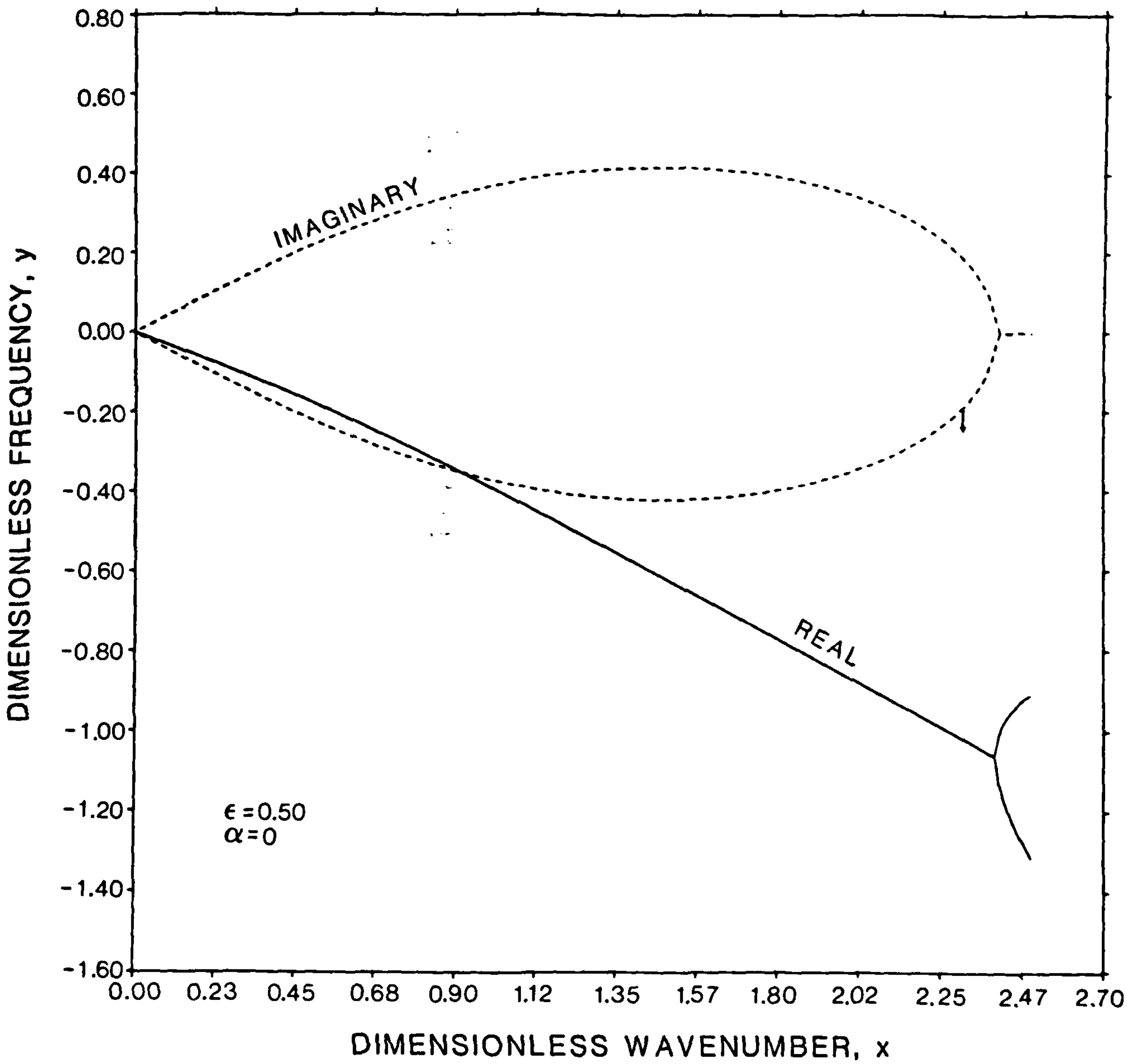
- Transforming these to physical variables, γ growth rate,

$$y_r = \frac{\omega}{\omega_B} = \epsilon^{\frac{1}{2}} \; ; \quad \epsilon = \frac{M_{ce}}{M_B}$$

$$\boxed{\omega = \omega_B \sqrt{\frac{M_{ce}}{M_B}} = \omega_{ce}}$$

$$y_i = \frac{\gamma}{\omega_B} = \frac{\sqrt{3}}{2^{5/3}} \left(\frac{M_{ce}}{M_B}\right)^{1/6}$$

$$\boxed{\gamma = \frac{\sqrt{3}\,\omega_{ce}}{2^{5/3}\,\epsilon^{1/3}} = \frac{\sqrt{3}}{2^{5/3}} \epsilon^{1/6} \omega_B}$$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-1.60
0.00 0.23 0.45 0.68 0.90 1.12 1.35 1.57 1.80 2.02 2.25 2.47 2.70
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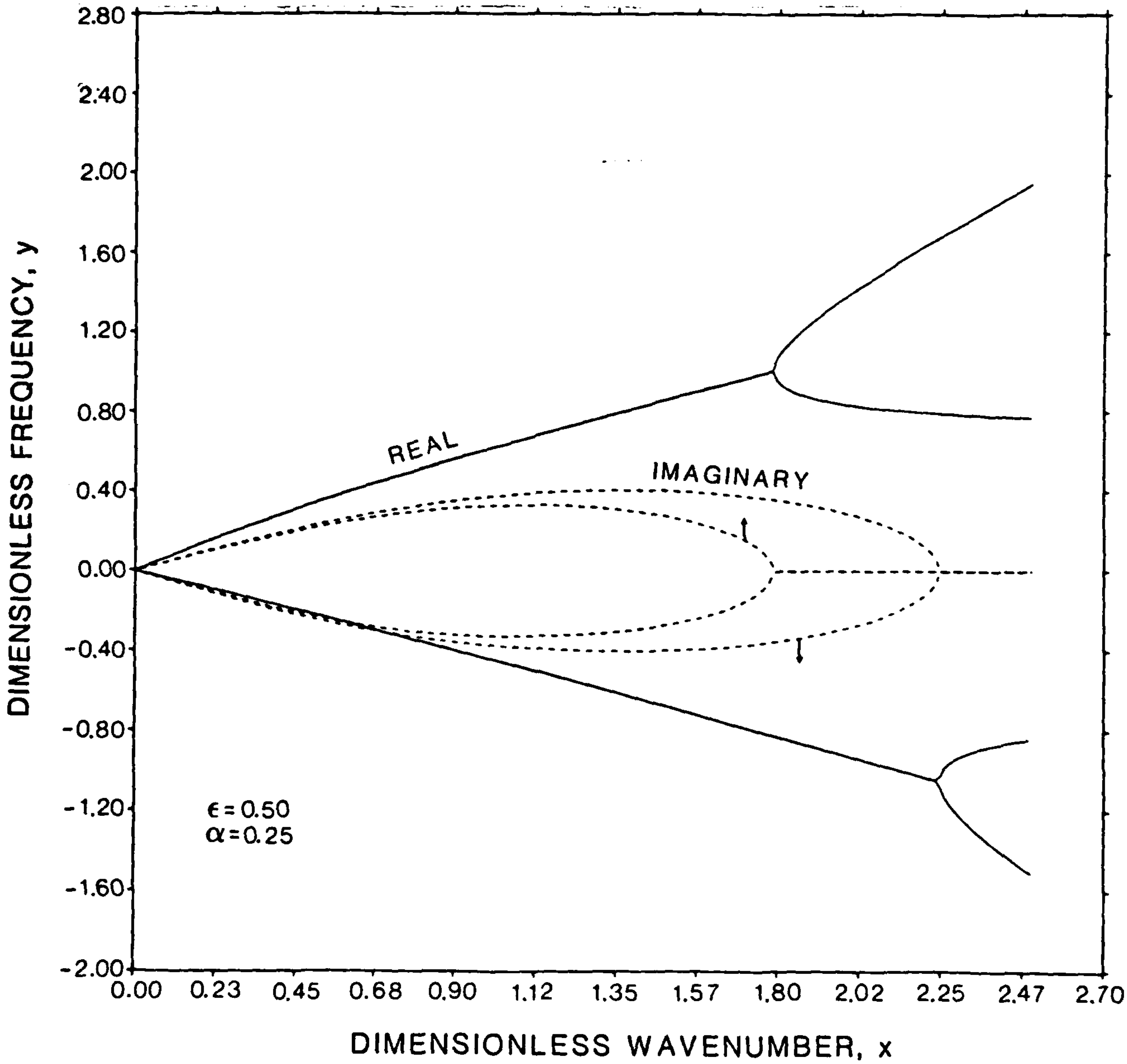
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DIMENSIONLESS WAVENUMBER, x
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0.68
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1.12
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1.80
2.02
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2.70
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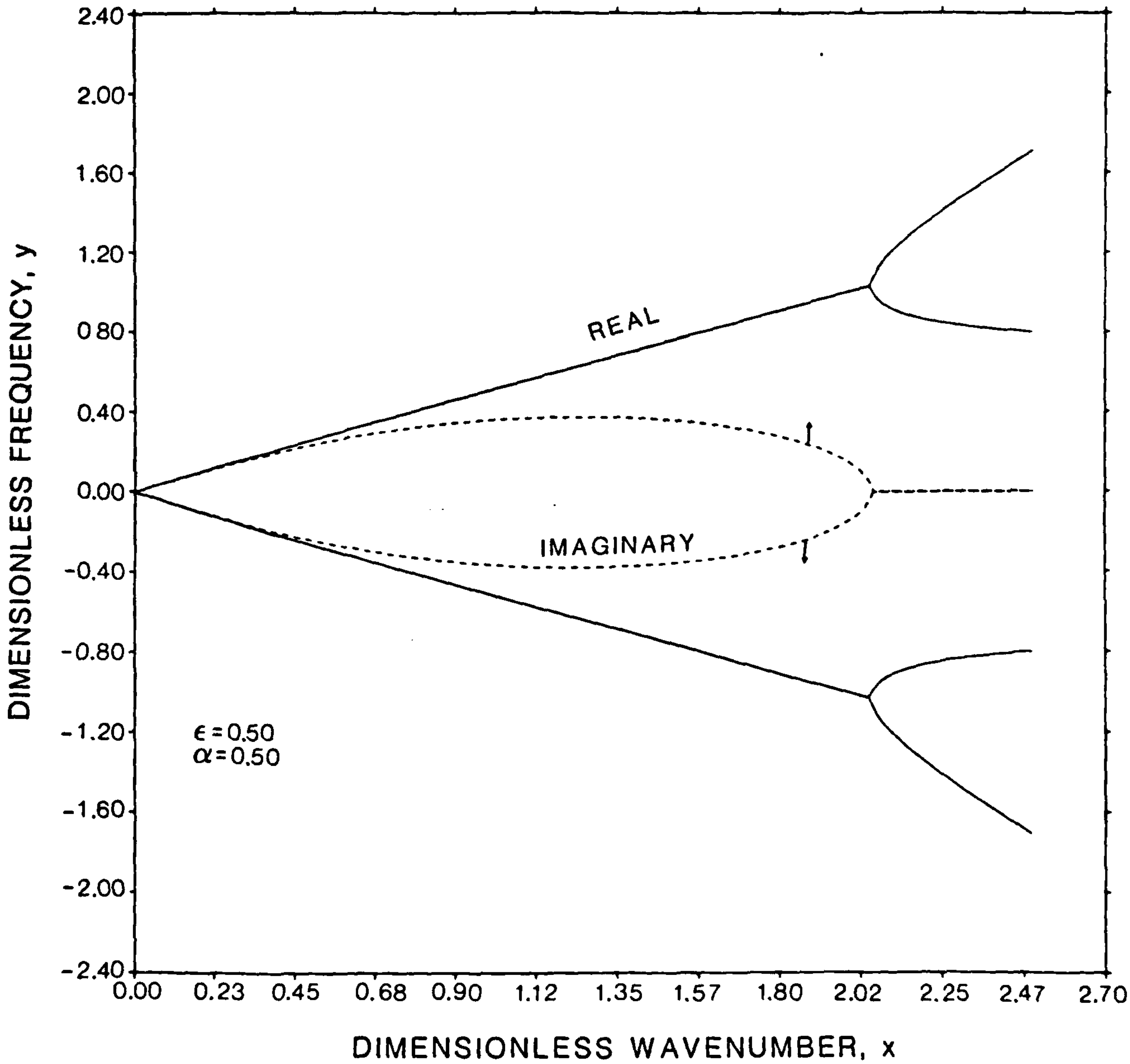
α = 0.25



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IMAGINARY
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α=0.50
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0.68
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1.57
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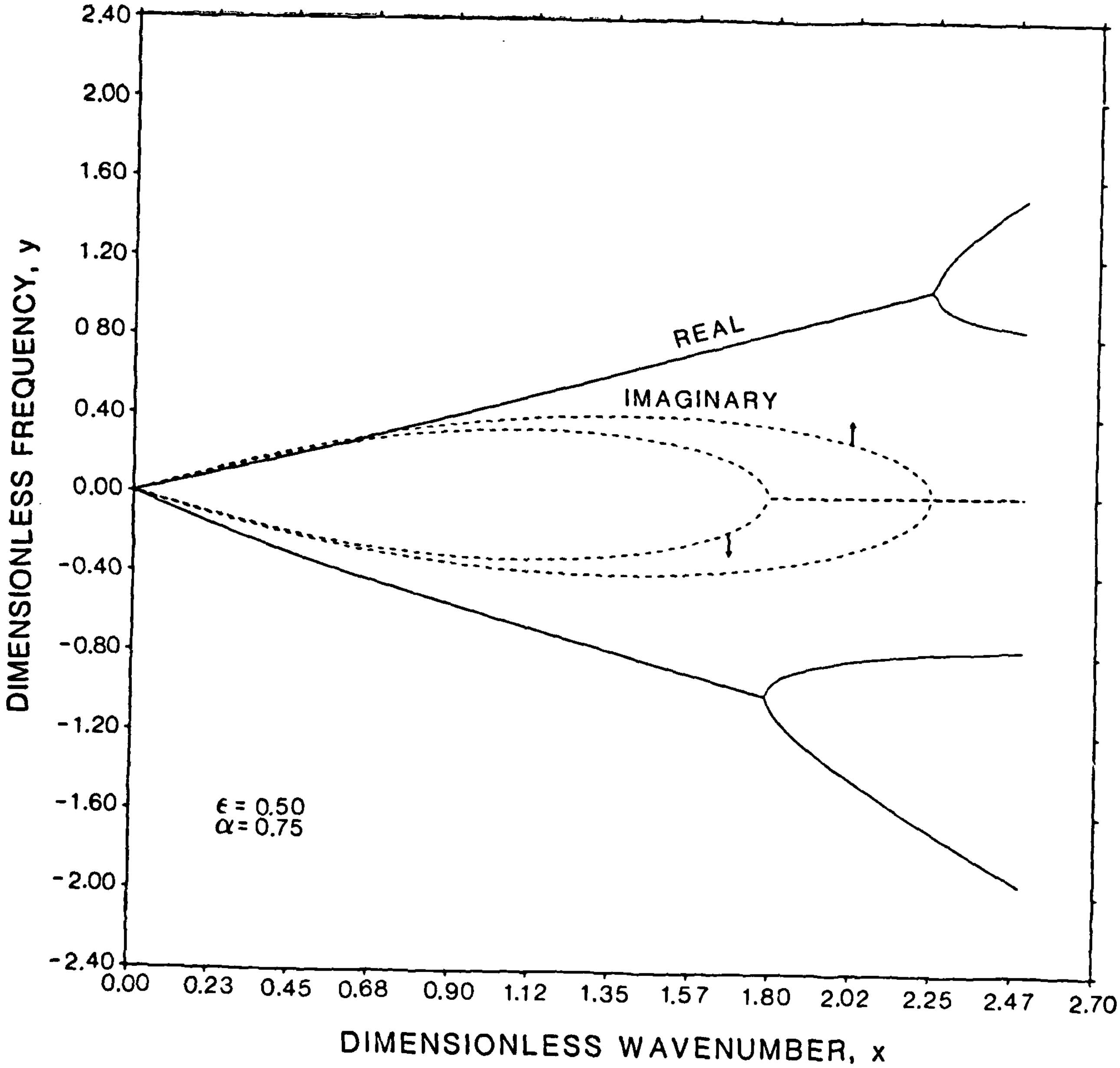
DIMENSIONLESS WAVENUMBER, x



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REAL
IMAGINARY
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0.90
1.12
1.35
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1.80
2.02
2.25
2.47
2.70
DIMENSIONLESS WAVENUMBER, x

Abstract Submitted for the

1985 IEEE International Conference on Plasma Science

Pittsburgh Hilton

June 3-5, 1985

RF Emission Power and Its Dependence on Plasma Parameters and Turbulence in A Classical Penning Discharge*

Mounir Laroussi, Paul D. Spence, David Rosenberg, John C. Mannone and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical Engineering
University of Tennessee
Knoxville, TN 37996-2100

We have operated a steady-state classical Penning discharge in a uniform axial magnetic field, the value of which can be varied up to 0.4 Tesla. The electron number density is typically 2 $10^9/cm^3$ in helium gas with Te = 5 - 10 eV. RF emission has been detected with specially developed broad-band planar-spiral and conical-spiral antennas[1], and its absolute integral power has been measured and plotted against electron number density and electron kinetic temperature, with the magnetic field as a parameter. The electron number density and kinetic temperature have been measured with a Langmuir probe inserted into the plasma.

The RF emission spectrum covers a broad-band frequency range between 100 MHz and 1000 MHz. This spectrum is formed by numerous harmonics of fundamental frequencies. The correlation between the RF emission spectra and the results already obtained on the electrostatic turbulence[2,3] due to strong axial and radial electric fields[4] and on wave propagation in the plasma is also investigated.

1. P. Spence, and J. R. Roth, paper 3R3, IEEE International Conference on Plasma Science, St Louis, Missouri, May 1984.

2. M. Laroussi, L. R. Baylor, P. Dehkordi, and J. R. Roth.: "Anomalous Drift Waves Detected with Microwave Scattering in an Electrical Field Dominated Plasma", Paper 1 W-4, APS Bulletin, Vol. 29, No. 8 p. 1197, (1984).

3. J. R. Roth, P. D. Spence, L. R. Baylor, D. Rosenberg, and P. Dehkordi.: "Correlation of RF Emission, Plasma Wave Propagation, and Plasma Turbulence in Classical and Modified Penning Discharges", Paper P 1-12, Proceedings of the International Conference on Plasma Physics, Lausanne, Switzerland, June, 1984.

4. R. L. Pastel, and J. R. Roth.: "Axial Electric Fields and Electron Number density Profiles in a Classical Penning Discharge", APS Bulletin, Vol. 23 No. 8, pp. 1256-1257, (1983).

*Supported by AFOSR contract 81-0093

Subject category and number:

17-Plasma Waves and Instabilities

☐ Prefer oral session

☒ Prefer poster session

☐ No preference

*Please schedule next to accompanying paper by Spence et.al.

Submitted by:

signature

J. Reece Roth
same name typewritten

University of Tennessee
company

Ferris Hall 409
address

Knoxville, TN 37996
city, state, zip

(615) 974-4446
telephone

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Abstract Submitted for the

1985 IEEE International Conference on Plasma Science

Pittsburgh Hilton

June 3-5, 1985

<u>Collisional Magnetic Pumping Revisited</u>*

J. Reece Roth and Mounir Laroussi

UTK Plasma Science Laboratory
Department of Electrical Engineering
University of Tennessee
Knoxville, TN 37996-2100

Collisional magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma, and driving it with relatively low RF frequencies which ultimately transfer energy to the parallel component of the ion velocity. For this form of heating to take place, the period of the driving RF and the collision time should be comparable, and both of these should be much less than the transit time of an ion through the heating region. Berger, et al.[1] have shown that if a sinusoidal perturbation of the confining magnetic field of the form $B = B_0(1 + \delta \cos \omega t)$ is applied, the heating rate is given by

$$\frac{dE}{dt} = \frac{\delta^2 \omega^2 \nu_c}{6(9\nu_c^2/4 + \omega^2)} E \qquad (1)$$

where ω is the driving frequency, ν_c is the collision frequency, $\delta << 1$ is the field modulation[2], and E is the total ion energy. Transfer of energy to the parallel component of the ion velocity occurs because the magnetic moment $v_\perp^2/B$ is approximately constant. There is a small net collisional energy transfer to this parallel component as the magnetic field varies sinusoidally, and the perpendicular components of velocity follow suit. In this original form of collisional magnetic pumping[1,2,3], the sinusoidal variation of $v_\perp^2$ about the mean established outside the heating region left only a very small net energy transfer, which is proportional to the square of the small parameter δ.

In this paper, we explore the consequences of applying to the exciter coil a RF current which is either full wave rectified, $B = B_0 (1 + \delta |\cos \omega t|)$, or which is a sinusoidal excitation with a DC bias magnetic field applied only in the axial region subtended by the exciter coil, $B = B_0 (1 + \delta (1 + \cos \omega t))$. In both these cases, the conservation of the magnetic moment will lead to an increase in the perpendicular components of velocity above the equipartition values outside the exciter coil, but not to a decrease. Thus any stochastic process, including collisions in the heating region, is much more likely to achieve a net energy transfer to the parallel velocity component. This should lead to a heating rate linearly proportional to the modulation δ, rather than to its square, as in Equation 1. If ions are scattered by fluctuating electric fields originating from strong plasma turbulence, this can lead to an effective collision frequency higher than the binary collisional value, and to greatly enhanced ion heating rates.

1. J. M. Berger, W. A. Newcomb, J. M. Dawson, E. A. Frieman, R. M. Kulsrud, and A. Lenard, <u>Physics of Fluids</u>, Vol. 1, No 4 (1958) pp. 301-307
2. K. Miyamoto, Plasma Physics for Nuclear Fusion, MIT Press, Cambridge, MA (1980) pp. 440-441.
3. T. Kammash, Fusion Reactor Physics, Ann Arbor Science Publishers, Ann Arbor, MI (1975) 161-182.

*Supported by the Air Force Office of Scientific Research, contract AFOSR 81-0093 (Roth).

Subject category and number:

13 Plasma Heating

☐ Prefer oral session

☐ Prefer poster session

☒ No preference

Submitted by [signature]

signature

J. Reece Roth

same name typewritten

Department of Electrical Engr.

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(615) 974-4446

telephone

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Dr Martin D Nahemow Conference Chairman Westinghouse R&D Center 1310 Beulah Road Pittsburgh Pa 15235

APPENDIX C

TRIP REPORT ON THE 1984 INTERNATIONAL CONFERENCE ON PLASMA PHYSICS, LAUSANNE, SWITZERLAND

Dr. J. Reece Roth
Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

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Dr. J. Reece Roth
Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

General Background

It was possible to set aside enough travel funds from contract AFOSR 81-0093 to cover my attendance at the 1984 International Conference on Plasma Physics which was held in Lausanne, Switzerland, from June 27 to July 3, 1984. The pecularities of the air fare structure made it possible to stay overseas two weeks, from June 23, to July 7, $600 more cheaply than the air fare which I would have had to pay to attend the conference alone. I therefore stayed in Europe the entire two weeks, and used the extra time to visit three additional laboratories. These laboratories include the French Fusion Research Laboratory at Grenoble, France; the Institute for Plasma Physics at Garching near Munich, West Germany; and the Culham Laboratory and the JET site, near Oxford, England.

In the report below, I summarize the invited papers at the conference, reprints of which will not be available for approximately six months; I describe a selected few of the poster papers which were of interest to me personally, mostly relating to plasma turbulence, beam-plasma interactions, and radiation from plasmas. Other contributed papers are available in the proceedings, which was handed out at the conference. Finally, I included a description of the site visits to laboratories which were part of the trip.

This meeting in Lausanne, Switzerland was a joint conference of the Sixth Kiev International Conference on Plasma Theory, and the Sixth International Congress on Waves and Instabilities In Plasmas. This meeting represented the third time, at intervals of two years, on which these individual conferences met jointly. Previous joint conferences in this series were held at Goteborg, Sweden, in 1982 (which I also attended and for which I wrote up a trip report), and in Nagoya, Japan, in 1980. More than 450 papers were presented at this conference by individuals from 39 countries. This

conference was sponsored by, among other organizations, the International Union of Pure and Applied Physics. It was a well-unified conference, in which there were no simultaneous sessions, with only invited review papers and topical papers in morning and afternoon oral sessions. These oral sessions were not held in conflict with the morning and afternoon poster sessions at which all contributed papers were presented.

This joint International Conference on Plasma Physics is restricted to the theory and experimental aspects of high temperature plasmas, with low temperature plasma phenomena being covered by the International Conference on Phenomena in Ionized Gases, which is held on odd-numbered years alternating with this conference. This conference was held in a major conference hall which provided more than adequate facilities for the conference sessions.

Invited and Review Papers

Unlike the contributed papers, there were no texts or even abstracts of the invited papers at the meeting. The invited papers are to be published by the conference organizers 6 to 9 months after the conference. The general review talks were offered in the morning between the hours of 9:00 and 10:30; each of two lecturers had about 45 minutes to present his topic. These were intended to be broad topics of wide general interest. From 10:30 to 12:30 the morning poster sessions were presented. After a break for lunch, the afternoon poster sessions were presented from approximately 2:00 to 4:00 in the afternoon. Starting at 4:00, there were sessions of invited papers on special topics. On most days, there were two concurrent sessions of invited special topic papers, and I report below on those which were of interest to me personally. The morning review papers, and many of the afternoon invited papers, were heavily biased toward fusion energy. The general content of the papers at this meeting was similar to that of the American Physical Society's Plasma Physics Division, except that some applications of high temperature plasma physics, like astrophysical plasmas, received more attention than they ever do at the APS Plasma Physics Division meeting.

Wednesday, June 27, 1984

On Wednesday morning, Alan Gibson from Culham gave a survey of recent results on ohmically heated plasmas in the JET facility, which is the world's largest tokamak, and the centerpiece of the European fusion program. The JET facility achieved its first plasma about one year ago, and has been operating as an Ohmically heated tokamak since that time. The objectives of the JET experiment have been broadened somewhat. By the completion of the project in 1990, they expect either to have a reacting DT plasma which is capable of burning in the steady state, or to show what must be done in order to achieve a burning plasma in a larger machine. The JET facility has been designed and built for remote maintenance, and so can burn deuterium and tritium for extended periods of time.

The primary issue in tokamak research at present is the scaling of the particle containment time, since there appears to be no question that densities and ion kinetic temperatures adequate for steady state fusion reactions can be achieved. The only open question is whether the individual ions can be contained long enough on the average so that net power will be produced by a DT plasma. The question of confinement time scaling is a very vexing one, since the physical process responsible for radial transport in tokamaks has not been identified thus far, and the scaling of the containemnt time with plasma parameters has been estimated in terms of various phenomenological scaling laws. The JET plasma is capable of operating with a circular or a D-shaped cross section. It appears that the vertical elongation is no help in obtaining longer containment times, based on experiments thus far with ohmic heating. Starting in 1985, they plan to add neutral beam heating and ion cyclotron resonance heating to the JET facility. There are no plans at this time for lower hybrid heating in JET. The parameters achieved thus far with ohmic heating are electron kinetic temperatures T_e approximately 2 keV, electron number densities of 2×10^{19} particles per cubic meter, and energy containment times of about 0.35 seconds.

A second general review talk was given on Wednsday morning by Thomas H. Stix, who presented an historical survey of plasma waves, which started with the observation of ionospheric whistlers in the military telephones that were used in World War I.

On Wednesday afternoon I attended the special topic session on MHD phenomena in tokamaks. These papers were concerned with the MHD activity which has been observed in tokamaks for some time, but only adequately understood in recent years. In tokamaks, the plasma acts as the single turn secondary of a transformer and carriers a very large toroidal current. This current not only heats the plasma by ohmic heating, but provides a poloidal magnetic field which assists in confinement of the plasma. Tokamak plasmas are unstable to a type of interchange instability in which the current channel and the plasma undergo filamentation. When these instabilities occur in the core of the plasma, they act as a mixing mechanism, and flatten the density and kinetic temperature profile of the plasma. When they occur at the edge of the plasma, they can disrupt the equilibrium of the plasma as a whole or, at a minimum, result in large bundles of the plasma hitting the limiter or walls and being lost from confinement.

In the first of three papers, K. McGuire discussed observations of finite-beta MHD phenomena in tokamaks. He was one of several tokamak researchers at this conference to report a new form of MHD instability, "ERP", a rather unfortunate acronym for "Edge Relaxation Phenomena", which occurs at high beta, and results in rapid, cross-field loss of plasma confinement. Various kink instabilities have been seen in high beta tokamaks with azimuthal mode numbers as high as four or five. When tokamaks are heated with such auxiliary heating methods as neutral beams, additional MHD instabilities are observed, the effect of which is to reduce the net efficiency of the neutral beam heating. In the Doublet-III tokamak and PDX experiments in the United States, between 20 and 40% of the input power is lost in the form of MHD instabilities which preferentially lose energetic beam ions before they have an opportunity to slow down and heat the plasma.

P.K. Kaw of India presented a theoretical paper on resistive tearing and ballooning modes in a high temperature plasma, which was addressed to problems of MHD instabilities in tokamaks which arise as a result of a finite electrical resistivity in the plasma. There has been renewed interest in this theoretical area, since experimental observations of tokamak plasmas are now pushing into a regime in which the older, infinite conductivity theory is

no longer valid. Kaw's paper was particularly interesting because he used quasi-thermodynamical arguments to reinforce and illustrate the practical consequences of the theoretical results which he presented. He treated tokamak plasmas as having a large free energy as a result of the ohmic heating current, and suggested that this free energy may drive such undesirable phenomena as anomalous heat transport and resistive ballooning modes.

Finally, L. Laurent of France discussed the nature of tokamak disruptions, by which he meant the same phenomena which McGuire had termed edge relaxation phenomena. He pointed out that they had observed on the TFR tokamak extensive MHD activity at the edge of the plasma, which manifested itself by a rearrangement of the radial profile of plasma density and kinetic temperature, as well as sudden plasma loss during the more violent disruptions. According to Laurent, there is no essential difference between major and minor disruptions, a distinction which had been put forward by some tokamak researchers earlier in the United States and Russia, but that he felt that tokamak disruptions or MHD instabilities differ only in amplitude and mode numbers, without being significantly different in their physical origin.

Thursday, July 28, 1984

In the morning, there was a review paper by B. V. Chirkov of the USSR on the subject "Intrinsic Stochasticity" in which he discussed the way in which a deterministic, Hamiltonian system in classical mechanics could take on or exhibit behavior which appeared to be chaotic or random in character. The confinement of charged particles in magnetic fields provides an example of this. As an exercise in classical mechanics, one can write the Hamiltonian for the motion of a charged particle in a static magnetic confining field, and derive equations of motion which appear entirely deterministic. However, the actual particle trajectories are very often so complicated, that one finds it difficult to make any general statement about in what volume of physical space the particle will be confined, or even whether it will be confined or not. Chirkov defined a random process or phenomenon as one which was unpredictable from observation and uncomputable, and in such a case one is

generally reduced to using statistical methods to describe it. He distinguished a random phenomenon from one exhibiting dynamical chaos, by which he meant a random motion of a completely deterministic system without noise.

The second review paper of Thursday was delivered by Richard Post who spoke on physics issues in mirrors and tandem mirror systems. He first reviewed the current state of the tandem mirror experiment at the Lawrence Livermore National Laboratory, and reviewed the physics of stability and confinement in such devices. He pointed out that the tandem mirror confinement geometry differs from the tokamak in having a confinement time scaling that is well understood in terms of the basic physical processes responsible, and is in good agreement with experimental observations.

The most interesting result which Post reported was that axial losses of charged particles from the tandem mirror geometry have now been reduced to such low levels that the major problem in the future for tandem mirrors will be the radial transport losses. This is an important milestone in tandem mirror research, because they have now achieved such low levels of end losses that they are in the same boat as the tokamaks and other toroidal confinement geometries, where radial transport provides the dominant particle loss. The major radial loss in the current tandem mirror is apparently drift losses, which arise in the end mirrors from azimuthal electric fields and fluctuating electric fields.

Post emphasized the importance of electrostatic potential control in the confinement of the tandem mirror plasma. I have been working for many years on electric field dominated plasmas, and on electrostatically assisted toroidal confinement, and so I was very pleased to hear that at least one national laboratory in the US recognized the potential importance of electric fields to plasma containment.

On Thursday afternoon there were several invited papers which I was not able to hear because of scheduling conflicts between the two concurrent sessions. However, I did attend the paper by Strelkov of the USSR, who reported recent results from the T-10 tokamak in Russa, the largest tokamak currently operating in the USSR. They have applied 1.2 megawatts of microwave power at a wavelength of 3.6 millimeters and a duration of 0.1 seconds for ECRH heating of the electron population in the T-10 tokamak.

They observed peak electron number densities up to 5 x 10^{13} particles per cubic centimeter, and they have also observed an energy replacement time which scales as the electron number density over the entire range of operation. I next heard a paper by H. Soltwisch from West Germany, who reported recent results from the Textor tokamak, a large tokamak which has been built at Julich at West Germany with cooperative participation from the United States. They have made careful measurements of the electrical conductivities in the Textor tokamak, and find that the electrical conductivity is somewhat below the Spitzer value.

I next attended a paper by W. C. Turner of the Lawrence Livermore National Laboratory who reported some details from the TMX-Upgrade thermal barrier tandem mirror experiment. In an attempt to understand the radial transport losses, they measured small potential fluctuations in the TMX-U plasma of approximately 1 volt rms in the central cell. In the central cell, the value of the plasma stability index beta has been as high as 30%. Thus far, classical 90° scattering of ions on hot electrons seems to explain the power balance. They hope ultimately to get to number densities of 2 x 10^{13} particles per cubic centimeter in the central cell of the TMX-U experiment; now they have densities of about 2 x 10^{12} particles per cubic centimeter.

Finally, Iuean R. Jones of Australia discussed the rotomak concept as a means of driving current in plasmas and creating spheromak plasmas. This is an approach which is the plasma analog of a squirrel-cage electric motor, in which a plasma in a long, uniform magnetic field is perturbed with a rotating, time-dependent magnetic field at right angles to the static, axial magnetic field. The perturbing magnetic field is caused to rotate aziuthally about the axis of symmetry of the magnetic field. This has the effect of inducing currents in the cylindrical plasma column which flow around the axis of the plasma and generate a spheromak configuration, which is roughly analogous to a smoke ring in ordinary hydrodynamics. These rotating magnetic fields can be easily set up by a phased, series of windings outside the plasma boundary, and represent a way of generating currents in plasmas which I expect to see widely imitated in the future.

Friday, June 29, 1984

The first of two invited review papers was by O. Gruber from West Germany, who spoke on confinement regimes in ohmically and auxiliary heated tokamaks. This paper documented the continuing attempt to find a scaling law for the energy replacement time of tokamaks, in the absence of a physical theory which predicts what this containment time should be. Tokamak plasmas that are heated entirely by ohmic dissipation have been shown to follow the "neo-Alcator" scaling law,

$$\tau_E = 7.1 \times 10^{-22} a R^2 n_e q^{\frac{1}{2}} \text{ sec } (CGS) \tag{1}$$

which is consistent with data from a wide variety of tokamaks all over the world. When additional heating mechanisms are applied, such as energetic neutral beams, or ion cyclotron resonance heating, the neo-Alcator scaling law no longer applies, and the containment time is generally less. Gruber reported results from the Textor tokamak, in which they have observed "ELM's", which are edged-localized modes, a form of MHD instability which they feel plays an important role in determining the energy confinement time of tokamaks. When they use auxilary heating, the particle containment time appears to scale as

$$\tau_E = 0.11 \, I A_i^{\frac{1}{2}} \text{ sec} \tag{2}$$

where I is the toroidal current in megamperes, and A_i is the ion mass. The size scaling is unknown at present, but the containment times calculated from Equation 2 above are well below those for neo-Alcator scaling.

The confinement picture at present is rather murky, but it appears that the addition of auxiliary heating to tokamaks provides an additional source of free energy which gives rise to instabilities (edge localized modes) at the edge of the plasma which carry large streamers of plasma away to the wall, and reduce the effective containment below levels predicted by neo-Alcator scaling. There is some hope in the situation however, since in a later paper, H. Furth pointed out that as experimenters become more familiar with the operating regime of their device, they can adjust the confinement time, under auxiliary heating, almost to the point which would have been predicted by

neo-Alcator scaling. It is very likely that scaling laws such as Equation 2 are more a reflection of the amount of experience of a particular research group with auxiliary heating, then it is of any fundamental limitation on the containment time in tokamaks. Nonetheless, expressions like Equation 2 (sometimes called Mirnov scaling) have been used to scale present experimental results on auxiliary heated tokamaks to levels appropriate for engineering test reactors or even power plant reactors. It may very well be that Mirnov scaling of Equation 2 is too pesimistic, and that the containment times actually achieved in engineering test reactors and power plant reactors will approach that of neo-Alcator scaling, given by equation 1.

The second invited review paper was by M. Kuperus of the Netherlands, who spoke on solar physics. He concentrated on plasma-related phenomena, including particularly the dynamo model for the solar magnetic field, and the 10.8 year solar sun spot cycle. He pointed out a fact of which I had not been aware, that there is now geological evidence that the 10.8 year solar sun spot cycle has been going on for millions of years. The physical process which maintains the solar sun spot cycle, and particularly which determines its period, is not at all clear. He pointed out that most structures in the photosphere and chromosphere of the sun (near its surface) are high beta plasmas, for which the plasma presure nkT, is nearly equal to the magnetic pressure, $B^2/2\mu_0$. The earth's magnetosphere is another example of a high beta plasma. The phenomena in the corona of the sun, however, is low beta. A particularly interesting implication of Kuperus's talk was that much conceptual and theoretical work remains to be done before the physical processes which occur on the sun can be said to be well understood.

On Friday afternoon, I attended the special topics session on the rf heating of plasmas. A paper was presented by G. A. Collins of Switzerland, who reported their first results on Alfven wave heating of the TCA tokamak at the Swiss Federal Institute of Technology in Lausanne. The TCA tokamak is a relatively small device with a major radius of 61 centimeters, and a minor radius of 18 centimeters. It is the only major experiment outside the Soviet Union which is devoted to Alfven wave heating. Alfven waves propagate in a magnetized plasma along the magnetic field lines, and are analogous to the displacement which occurs when the string of a musical instrument is

plucked. The more dense the plasma, or the more massive the ions, the higher the effective mass per unit length of the string, and the lower the frequency. The plasma-physical equivalent of plucking the plasma ions trapped on magnetic field lines is excitation by an antenna at a few megaHertz or a few 10's of megaHertz. These antennas were set up in the TCA tokamak, and they are now capable of coupling a significant amount of power to the plasma (hundreds of kilowatts). The results are still very preliminary, but the TCA group has reported increasing both the electron and ion kinetic temperature by 50% above the ohmically heated values with Alfven wave heating.

We next heard from G. Melin of France, who reported on lower hybrid heating in the Petula-B tokamak at Grenoble. This also is a relatively small tokamak, with a major radius of 72 centimeters, and a plasma radius of 16.5 centimeters. They have operated this tokamak over a number density range from 0.5 to 10 x 10^{13} particles per cubic centimeter. In their low density, lower hybrid current drive experiments, they also observed a limit on current drive effectiveness at a density limit of approximately 3 x 10^{13} particles per cubic centimeter. At densities above this limit, lower hybrid rf power is ineffective at driving the ohmic heating current, but it is effective at heating the plasma. At electron densities above 6 x 10^{13} per cubic centimeter however, even the heating efficiency declines with increasing electron number density. These limitations of lower hybrid heating and current drive are worrisome, since engineering test reactors and power plant reactors must operate at number densities somewhat above 10^{14} particles per cubic centimeter in order to produce adequate power densities and a net power output. The Petula discharge is subject to "kinetic disruptions" during the lower hybrid heating of the plasma. These look like the conventional internal mode disruptions of an ohmically heated tokamak, but are triggered by the external energy input of lower hybrid heating.

R. Wilhelm of reported on the application of electron cyclotron heating (ECH) to the Wendelstein-7A stellarator at Garching. The Wendelstein-7A stellarator has an L = 2 (with an oval plasma crossection), a confining magnetic field of 1 tesla, a characteristic plasma radius of 9 centimeters, and a major radius of 2 meters. The heating efficiency approaches 50% for ECH heating of this plasma. It is possible to adjust the degree of shear and the

rotational transform angle in this stellarator because it has a set of separately adjustable toroidal field coils and helical windings. They find that confinement is best when the magnetic field lines do not close on themselves after one or a few circuits around the major circumference of the torus; these rational drift surfaces lead to charge separation, the buildup of electric fields, and enhanced plasma drift velocities.

<u>Saturday, June 30, 1984</u>

Dr. N. Sato of Japan gave an invited review paper on the formation of electrostatic potentials in a magnetized plasma. He described some experimental work, done in his own laboratory, and reviewed the current status of double layers, which have been a subject of active interest in astrophysics and at the previous International Conference on Plasma Physics at Goteborg, Sweden, two years ago. Double layers are steep potential profiles or strong electric fields which exist in flowing plasmas which are confined in uniform or mirror-like containment geometries. This paper was of particular interest, since we have observed strong axial electric fields in our modified Penning discharges, on the order of several hundred volts per centimeter. In our case, these strong axial electric fields do not appear to be double layers, but originate from the high, anomalous electrical resistivity which is characteristic of the highly turbulent discharges investigated in our laboratory. The subject of stationary double layers was explored in a workshop following the Goteborg conference two years ago, and seems to be well understood both theoretically and experimentally.

Sato pointed out that current interest in this area relates to moving or fluctuating double layers, which have been observed in several recent laboratory experiments, including his own laboratory, and one at UCLA, for example. Unlike the plasmas in our laboratory at UTK, the total potential drop across a double layer is usually a few times the electron kinetic temperature in electron volts, with electric fields from one to ten volts per centimeter. In Sato's experiment, he found what he interpreted as a fluctuating double layer, and that the electric field, voltage drop, and a decrease in the current flowing from one end of the plasma to the other was associated with the onset of current and potential fluctuations which were

strongest in the region of highest electric fields. These results sound very much like the transition to turbulence observed in our own series of experiments.

By having counterflowing plasmas originating from each end of a long cylindrical magnetic field, Sato was able to do controlled experiments on the behavior of double layers. An interesting such experiment consisted of moving the position of a perturbing magnetic field coil along the axis of the otherwise uniform, constant magnetic field, and by doing so Sato was able to move the position of the double layer along the plasma. This agrees with some of our observations at the UTK Plasma Lab, since we observe higher axial electric fields in the modified Penning discharge, which is operated in a magnetic mirror geometry, than in the classical Penning discharge, which has a constant axial magnetic field.

Also on Saturday morning, we heard an invited review paper by D. Pesme of France, who spoke on wave-particle interactions and plasma turbulence theory. This also was a topic of personal interest to me because of my long-standing interest in plasma turbulence. He presented a review of the classic theory of plasma turbulence originated by DuPree and Kadomtsev, which is based on normal mode analysis and resonant wave-particle interactions. The quasi-linear theories have no mode coupling terms, which is unrealistic in the face of a broad range of laboratory data which indicates significant mode coupling. He discussed at great lengths the significance of Gaussian versus non-Gaussian statistics for fluctuations in a plasma, particularly fluctuations of the electric field.

In making plasma turbulence measurements in the past, I have often seen Gaussian amplitude statistics for electrostatic potential (actually, electric field) fluctuations, but it has also been possible to observe experimental conditions for which the amplitude statistics of the fluctuations departed substantially from Gaussian form. Experimentally, there appear to be no great qualitative or even quantitative difference between the plasma properties and transport coefficients associated with Gaussian versus non-Gaussian statistics, so his contention that this was a significant physical distinction did not appear to be very convincing to me personally. I commented on this in the discussion period, and he replied that his comments

were restricted to two dimensional turbulence. I pointed out that the data which I had observed was in fact a three dimensional experiment. After this exchange, several individuals in the audience came up to compliment me on having injected a note of reality into the discussion.

In the afternoon special topics session, J. Cary discussed some of the problems of stellarator confinement. It appears that the principal difficulty with stellarator theory is that in the steady state, they do not have an axial, ohmic heating current flowing in the plasma, and so there is no J x B body force on the plasma arising from that source which allows one to conveniently study its equilibrium properties. From a theoretical point of view, stellarators are difficult to study also because of their lack of symmetry and the absence of a rigorous plasma equilibrium theory. Cary described a relativistic electron beam with a small angular spread, less than 10°-how much less he did not say-and remarked that the same relativistic electron beam experiment dissipated its energy in several meters, I assume in air. Kodian described the INAR magnetic mirror device at Novosibirsk, which is operated in a magnetic field of 2.5 tesla, with a maximum magnetic field of 4.2 tesla, and a length of 2.4 meters. The plasma radius is 3 to 4 centimeters. The number density is very high, and ranges from 10^{14} to 10^{16} particles per cubic centimeter. This is apparently a cross-field device like the old "Burnout-5" device at the Oak Ridge National Laboratory. Into this plasma, they apparently injected a 1 MeV, 25 kiloamp relativistic electron beam, the pulse length of which was 50 to 70 nanoseconds. The beam number densities ranged between 2×10^{11} and 2×10^{12} particles per cubic centimeter. They found that after interacting with the plasma, the beam loses energy, and increases its angular spread. They found much microwave emission at number densities below 10^{14} particles per cubic centimeter. Kodian reported a rather surprising result that the microwave emission came out at <u>twice</u> the electron plasma frequency, whereas in our own beam plasma interaction experiments here at the UTK Plasma Science Laboratory, we find that most of the microwave emission is in the vicinity of the electron plasma frequency itself.

Monday July 1, 1984

One of the invited review papers on Monday morning was by Harold Furth of Princeton, who spoke on the Princeton tokamak program. He spent most of his time reporting the most recent results of the TFTR ohmic heating experiments. So far they have had ohmic heating currents up to 1.5 megamps, (about half the maximum achieved by the JET experiment) toroidal magnetic fields up to 2.7 tesla, which compares with designed currents of up to three megamps and 5.2 tesla. The TFTR has operated with one second of constant, "flat-top" magnetic field. They have found that the loop voltage (the voltage which drives the ohmic heating current) is still varying after 1 second. The 1 second duration is a limitation of the power supply; the fact that the loop voltage is still changing after one second is an indication that they have not established a steady state, and that the machine was designed with an inadequate capacity to do so.

They routinely observe sawteeth and other forms of transient MHD phenomena in the TFTR, and have achieved electron kinetic temperatures of 1.5 to 2.0 keV with ohmic heating alone. They find that the energy containment time under ohmically heated conditions follows the neo-Alcator-like scaling law

$$\tau_E = 10^{-20} n_e R^2 a \, q^{0.8} \quad \text{(MKS)} \qquad (3)$$

where the geometric dependence is not clear, since all the tokamaks at Princeton have the same aspect ratio. The geometric dependence could be any combination of powers of a^α and R^γ where $\alpha + \gamma = 3$.

Furth described the conversion of the PDX poloidal divertor experiment to the PBX, the Pringeton Bean Experiment, which is a verticaly elongated tokamak plasma, the cros section of which has an indentation on the inside circumference, which provides increased stability of the plasma. In his talk, Furth incorrectly attributed this bean-shaped tokamak configuration to Mercier, rather than to William Bass and the topolotron group at Brigham Young University in Provo, Utah. On theoretical grounds, stability of tokamak plasmas with a bean-shaped cross section may be possible up to beta values of 20%.

The second invited review paper of the day was by H. Wobig from the Institute for Plasma Physics in Garching, who summarized recent work on stellarators, torsatrons, and heliotrons. One of the interesting features of the Wendelstein VII-A stellarator at Garching is that they have achieved very high number densities, in excess of 10^{14} electrons per cubic centimeter, at the same time that they have achieved ion kinetic temperatures, by neutral beam heating, of 1 keV. In a similar device in Japan, the Heliotron-E, values of the plasma stability index up to 3.7% have been observed.

Wobig listed the problems of the classical stellarator as being 1) Impurities: Since no ohmic heating currents are required, in the steady state impurities have the opportunity to build up to levels much higher than occur in tokamak experiments which are pulsed and of a shorter duration. 2) Stellarators have too low a value of the plasma stability index beta to be practical for a reactor, 3) They have finite beta effects, which occur at values of the plasma stability index of a few percent, that are detrimental to confinement; 4) The confinement of stellarators appears to be consistent with the neo-Alcator scaling of tokamaks, rather than neo-classical confinement; and 5) The classical stellarator does not have a modular coil system and is too complex to be disassembled by remote handling techniques. He described the Wendelstein VII-AS, the suffix "AS" standing for advanced stellarator, which is being built at Garching, and will go into operation in two years. This advanced stellarator is being built with modular coils, and with a confining magnetic field configuration which should allow higher values of beta than the classical stellarator.

On Monday afternoon there were a series of papers on gyrotrons and other cyclotron masers. A. Goldenberg of the USSR gave a survey paper on gyrotron research in the USSR. He is from the city of Gorky, which apparently is a center of gyrotron research. Much of his lecture was tutorial in nature, to provide background information for those of us in the audience who were unfamiliar with the current state of gyrotron technology. He cited the performance characteristics of some gyrotrons that apparently are under development in the USSR. He cited a particular test gyrotron intended to operate at a wavelength of 3 millimeters and deliver 2 megawatts in 100 microsecond pulses. He mentioned that another gyrotron was being developed

for the T 10 fusion experiment to operate CW, at a level of 1 megawatt at 3.6 millimeters.

Goldenberg then proceeded to describe a rather intriging series of experiments that were conducted at one atmosphere, in which the gas was irradiated with microwaves at 8 millimeters at power levels that range from below 1 kilowatt per square centimeter to values greater than 30 kilowatts per square centimeter. Apparently the objective of this investigation was to maintain a microwave-created fireball in a gas at 1 atmosphere, the purpose of which was not specified.

G. L. Granatstein of the Naval Research Laboratory then gave a paper on Gyrotron and other cyclotron masers, their present capabilities and future prospects. He pointed out that in the United States, a 1 megawatt cw-tube was now under design, and otherwise described the current state-of-the-art in the United States.

Tuesday, July 3, 1984

John Dawson of UCLA gave one of the more interesting invited talks of the conference, entitled "Collective Particle Accelerator". The device which he described was a plasma-based method of accelerating charged particles to TeV energies. This method is based on using an electron space-charge wave, the phase velocity of which travels with very nearly the speed of light. He proposes to trap positive particles, which it is desired to accelerate to high energies, in a trough of such a space charge wave and then, as the wave propagates at nearly the speed of light, the positive charge would be accelerated up to very high energies, depending on how nearly it approaches the speed of light. This plasma based method of particle acceleration has been checked by numerical simulations done by Dawson and some of his colleagues at UCLA and in the particle accelerator community. Dawson calculates that intense electric fields as high as 10^9 volts per centimeter may be possible, and this compares with about .2 MV per centimeter in the Stanford Linear Accelerator. Dawson calls this new concept the "surfatron", since the acceleration mechanism is roughly analogous to that of a surfboard riding in a wave, with the wave propagating very close to the speed of light. The plasma acceleration mechanism in this concept is over with too quickly for any

instabilities to develop, and Dawson calculates that protons should be capable of being accelerated to TeV energies in distances of a few tens of meters. This is a very interesting idea, and will probably be worth a Nobel prize if it works, since physicists have gone about as far as they can go with building ever-bigger conventional particle accelerators.

The second invited review paper was by J. G. Lominadze of the USSR, who spoke on plasma instabilities in the magnetosphere of a pulsar. He described the current "standard model" of pulsars, which is invoked to explain the various phenomena observed in pulsar emissions. The standard model contemplates pulsars which rotate rapidly enough, and have a high enough internal electrical conductivity, that the magnetic field on their surface is between 10^{12} and 10^{13} gauss. It seems that pulsars radiate about 1% to 0.1% of the total rotational energy which they lose. This rotational slowing can be measured in the lengthening of the pulsar period. A recent development in pulsars was the observation of a pulsar outside our galaxy in the large Magellanic cloud, with a period of 0.9 seconds.

The standard pulsar model was put under a very serious strain recently with the observation of a millisecond pulsar, a pulsar which supposedly is rotating so rapidly that it has a rotational period of 1.5578 milliseconds. This represents a rather incredible object, and in the discussion after his paper I asked Lominadze how short a period a pulsar would have to have before astrophysicists would be willing to abandon the standard pulsar model. He replied that this millisecond pulsar was right at the limit, because if pulsars having any shorter duration were observed, it would not be possible to explain how they could hold together under the centrifugal forces acting their surface.

CONTRIBUTED PAPERS

I found it very hard to document the contributed papers at the Lausanne conference, beyond the four page abstracts which appeared in the contributed conference proceedings distributed at the meeting. These four page papers were published in two volumes, and are available in my office if further information is desired about any one of them. The proceedings versions were generally out of date, with respect to the poster materials actually presented at the conference. However, almost none of the authors of poster papers

brought along copies of their poster materials or more extended reports for distribution.

My own paper entitled "Correlation of RF Emission, Plasma Wave Propagation, and Plasma Turbulence in Classical and Modified Penning Discharges" was a comparison of the results in these areas from the Navy and Air Force contracts which are being supported at the UTK Plasma Science Laboratory. I reported not only our experimental results on RF emissions, but also described some of our diagnostic methods, including our recently-developed broadband antennas which are calibrated in such a way that we can make absolute measurements of radiated power from the plasma, over the frequency range from 100 megaHertz to 1.2 gigaHertz. I was gratified by the interest shown in our work. There was a constant flux of people passing our poster, and many interested questions on the details of the physics and on our diagnostic techniques. We are using enough new, sophisticated, or unfamiliar diagnostic techniques that many of our methods were new to many at the conference. Our broadband antenna attracted particular interest, since, as far as I know, no one else in the field is using such sophisticated antenna technology to measure rf plasma emissions. One disappointment about my own paper was that it was scheduled on the first session of the conference on Wednesday morning, and the Russians did not arrive until late Wednesday afternoon. I was thus deprived of the opportunity to interact with any Russians interested in my work. In a concurrent poster session Wednesday morning, there were several papers on low frequency waves and turbulence, most of which represented rather small incremental advances over what has been known in this area for some time. A particularly interesting plasma turbulence paper was presented on Wednesday afternoon by E. J. Powers and his students from the University of Texas in Austin. In a paper entitled "Turbulence and Energy Cascading in the Edge Plasma of the Text Tokamak" they made measurements of the fluctuation-induced transport rate inside, and outside the limiter radius of this tokamak. They were able to show, at least in the plasma boundary, that the fluctuation induced transport was of the proper magnitude and sign to account for the radial transport losses in this tokamak. They also carried forward the theory of turbulent fluctuations and used a sophisticated statistical argument based on the bispectrum to identify the

direction of energy cascading in the turbulent spectrum. In their case, they had a low frequency peak below 100 kiloHertz which seemed to be feeding energy both to lower and higher frequencies. The nature of this energy input peak frequency was not identified in these measurements, but it is clear that this Texas group is getting very close to the fundamental physical processes responsible for mode coupling and radial transport in tokamaks in general.

Compared to other and previous conferences, there were many fewer papers on laser-related plasmas, and relativistic electron beams. There also were relatively few papers on astrophysical topics, which had been a dominant theme in the preceeding conferences in this series.

There were contributed papers at this conference from both the EBT S group at the Oak Ridge National Laboratory, and from the Nagoya Bumpy Torus group, which was presented by its Principal Investigator. Ikegami. The Nagoya group had some very exciting results to report from their bumpy torus; recent application of a slow wave antenna allowed them to couple ICRH power into the Nagoya Bumpy torus plasma and achieve, on a pulsed basis, number densities up to 10^{13} per cubic centimeter, and ion kinetic temperatures of several hundred electron volts. These results suggest that cancellation of the EBT S experiment at Oak Ridge may be premature.

One of the dominant themes of this conference has been the increasing realization by both theorists and experimentalists of the role of electric fields and electrostatic potential wells in magnetized plasmas. In the past, the description of most devices ignored plasma turbulence, or the effects of electrostatic turbulence; it was also assumed that radial transport and confinement occured in the absence of any radial electric fields. This is no longer the case. Theoretical models are now attempting to include radial electric fields; and many experimentalists, particulary those with relatively modest experiments in underdeveloped countries, are turning their attention to plasma turbulence and its effects.

LABORATORY VISITS

Because of the savings possible on air fares by staying in Europe 2 weeks or longer, I was able to fit in three laboratory visits before and after the conference, which lasted from Wednesday June 27, to Tuesday, July 3. I also

was able to visit the tokamak laboratory at the Swiss Institute of Technology in Lausanne, which visit took place on Monday July 2 during the conference.

<u>Visit to Grenoble, France, June 25, 1984</u>

The city of Grenoble is located in south-eastern France, about 70 miles south of my air arrival point at Geneva. I traveled to Grenoble on Sunday, June 24, by train, to visit the high temperature plasma and fusion related research activities situated at the French Atomic Energy Commission's laboratory in that city. At present, Grenoble is one of two major centers of high temperature plasma physics and fusion research in France; the other is located at Fontenay-Aux-Roses, a suburb of Paris. The Grenoble laboratory was set up approximately 15 years ago when the fusion research group then at Saclay (another suburb of Paris) was moved to Grenoble.

I found the French fusion effort, and those participating in it, in some disarray. As part of a long-term plan for fusion energy in France, the French government has decided to move all fusion research fromFontenay-Aux-Roses and Grenoble to the southeastern city of Cadarache (Cad-a-rash), a small village about 30 miles or so north of Marsailles on the Medetirranian coast. The appeal of Cadarache apparently is that it is an economically depressed area that the central government wishes to stimulate, and located there is a major hydroelectric power facility, which is capable of meeting the power demands of large-scale fusion experiments of the future. Apparently neither Fontenay-Aux-Roses or Grenoble offer such capability. It is the intent of the French government to develop Cadarache into a viable site either for the <u>N</u>ext <u>E</u>uropean <u>T</u>orus (NET, the next step beyond the largest current tokamak experiment in Europe); or for the demonstration fusion reactor that is envisioned as being the next step beyond NET.

To make this move from the Paris suburbs and Grenoble (both of which are very desirable sites from the perspective of the people now working there) to the remote village of Cadarache, the French government has committed itself to build a very large superconducting tokamak experiment in Cadarache, called Tor-Supra. This device is very impressive, approximately the size and capability of the TFTR experiment at Princeton, but capable of being operated in the steady state. The Tor-Supra is seen as a technology

development project, and the staff members with whom I spoke see very little physics being accomplished in this device. It seems that the staff members of the French fusion program are very unhappy about making this move to a remote village, and many of them intend to go into other fields rather than make the move.

While at Grenoble, I was able to inspect one of the sectors of Tor-Supra which had been sent to Grenoble for vacuum leak testing subsequent to their manufacture. When these sectors past this test, they will be shipped to Cadarache for assembly. The schedule of this activity is to shift the staff from Fontenay-Aux-Roses and Grenoble to Cadarache over the next two years, with the transfer and setting up of the new laboratory to be complete two years from now. At about that time, the Tor-Supra facility is to go into operation. It is well along, judging from the hardware under test that I observed at Grenoble. While at Grenoble, I spent some time with Dr. G. Melin, who is one of the senior investigators on the Petula-B tokamak, the only large experiment currently in operation at Grenoble. This small tokamak was originally built in the mid 1970's to test transit time magnetic pumping as a heating mechanism. This was abandoned several years ago in favor of lower hybrid heating, to which the Petula experiment has been dedicated since about 1980.

At one time there was a second tokamak in operation at Grenoble, the WEGA tokamak, which has been moved to another site. Probably because of the small size of the Petula tokamak, the research group at Grenoble had several years of difficulty with contamination and impurities in their plasma. These problems have only recently been overcome by the use of low-Z limiters, extensive discharge cleaning, and bakeout of the vacuum vessel. The Petula-B experiment is well instrumented with diagnostic devices, which are capable of measuring the amount of lower hybrid heating which actually occurs. They have a pulsed klystron, which is capable of delivering more than one megawatt for periods of a few tens of milliseconds. They have seen both lower hybrid heating, and lower hybrid current drive in the Petula device, the specific results of which were summarized in my discussion of Melin's invited talk, contained in a previous section of this trip report. Like the experiments at Princeton, and at MIT on the Alcator, they observed an upper density limit

in the mid 10^{13} per cubic centimeter range, beyond which coupling of lower hybrid power to the plasma declines. In the Petula experiment, they also see the same scaling law for the coupling of the lower hybrid power to the toroidal current, when the lower hybrid power is used as a current drive. Their most important contribution to lower hybrid heating technology has surely been the development of phased waveguide arrays, in which the phase difference between adjacent waveguides are produced by baffles in the waveguide structure, and not by phase differences introduced by modulating the klystrons, or the geometric length of the waveguides. These baffle-like structures inside the waveguide are capable of providing phased microwave power, while being fed with a single klystron, a considerable advance over the complex waveguide arrays found in many other tokamak experiments.

Other activities at Grenoble include the vacuum testing of the Tor-Supra sectors before shipment and installation at Cadarache. These sectors are very large and impressive, and are approximately the size of the sectors of the TFTR. These are the vacuum can which will surround the confinement volume of the Tor-Supra tokamak, and do not include either the superconducting coils, or the mechanical structure of the Tor-Supra facility.

Also at Grenoble there is an effort on surface studies, in which an ion source in a belljar bombards samples of candidate wall materials at normal inccidence and at 45°. Most of the samples studied thus far have been light elements or low-Z materials; the individual with whom I spoke did not seem to be aware of the fact that the sputtering yields and electron emission coefficients of high Z materials like molybdenum and tungsten were much lower than that of low-z materials. Apparently there is no activity at Grenoble on the Next European Torus.

The researchers at Grenoble apparently hope to apply their expertise with lower hybrid heating and current drive on Tor-Supra, although the present plans envision only enough lower hybrid power to supply 1/3 of the current required on Tor-Supra, not enough to sustain the current by rf current drive alone. At present, it seems that there are no plans for lower hybrid heating or current drive on JET; although several of the people that I talked to at Grenoble, at Garching and at Culham were a little shifty about this, since the increasingly promising results of lower hybrid heating and current drive

make such an application increasingly attractive. There are a number of recently assigned engineers busy at Grenoble on technology-related matters, including the large radio transmitters for lower hybrid heating on Tor-Supra, the cryogenic refrigerators and dewars, and other of the strictly engineering aspects of Tor-Supra.

When complete, the Tor-Supra will be the largest superconducting tokamak in the world, and one of the largest tokamak experiments anywhere. It will, I believe, be comparable in size to the Russian T-15 tokamak, and probably will go into service before the T-15 is on line. The French government sees the Tor-Supra as not only a way of keeping the French fusion effort credible on a European wide basis, but establishing the credibility of the Cadarache site for future generations of fusion experiments. The role of the Tor-Supra will probably be similar to that of the TFR tokamak, which represented a previous attempt by the French governemt to put all of their eggs in one basket in fusion energy. The TFR tokamak was for several years the largest tokamak in the world, until the PLT came on line in the late 1970's.

Visit to the TCA Tokamak At Lausanne, Switzerland, Monday, July 2, 1984.

As part of the conference, the local organizers arranged a tour of the small TCA tokamak at the Swiss Federal Institute of Technology in Lausanne on Monday during the conference. I took the afternoon tour, since few of the poster papers in that session were of interest to me. The TCA tokamak is supported ultimately by Euratom, and as such is a part of the coordinated European fusion effort. This tokamak went into service about 1981, and for several years was plagued with impurities and plasma-wall interaction problems which kept it from meeting its potential in terms of electron temperatures, confinement times, etc. It is a rather small tokamak, located in an experimental bay at the Swiss Federal Institute of Technology which is much too small for the experiment. Externally, at least, it is the cleanest tokamak that I have seen. Everything in the laboratory was extremely orderly, in its place, and it looked like the entire laboratory had been steamed cleaned immediately prior to our visit.

The TCA tokamak operates at toroidal magnetic fields of 1.5 Tesla, ohmic heating currents of 180 kiloamperes, and it has achieved number densities up to 5 x 10^{13} particles per cubic centimeter. The research topics to which it is particularly devoted include Alfven wave heating, of which it is almost the only large scale example outside the USSR; and collective Thomson scattering, a diagnostic development project which is attempting to measure ion kinetic temperatures using Thomson scattering in the far infrared. The Thomson scattering experiments are just beginning to produce data, and in the few months before the conference, they saw signals which they felt were definitely above the noise level, although not with signal to noise ratios which allowed quantitative measurements of the ion temperatures. Their worst problem with collective Thomson scattering was the detection of very faint scattered signals at far infrared wavelengths, where liquid helium cooled detectors are needed in order to measure the very faint scattered signals. The Alfven wave heating experiments are moderately successful, with a rather high percentage (above 50%) of the power supplied to the Alfven wave antennas actually being coupled to the plasma, and resulting in measurable plasma heating. The exact, quantitative degree of heating will be better known when the collective ion Thomson scattering experiment is fully operational and capable of yielding the ion kinetic temperatures.

Visit to the Max-Planck Institute for Plasma Physics, Garching, West Germany, on July 4, 1984

Several of the individuals with whom I wished to visit at Garching, including Dr. Arnolf Schluter, and Dr. G. Greiger, were on vacation and not available. However, I spent the full day at Garching, and was able to see all of the major experimental research projects now in operation.

Garching is the headquarters of the NET (Next European Torus) design team, which is headed by Dr. R. Toschi, who until about 1 year ago was the Director of the Italian fusion research laboratory at Frascati. The European authorities set up a design team for the next European Torus in early 1983. According to Dr. Toschi, this effort really got started in the summer of last year, and the staff has now built up to a level of about 20 persons, and is increasing rapidly in size at the present time. The time schedule is long term,

in that by about 1988 they are to come up with recommendations as to the objectives and general configuration of the NET device, but approval to spend the n aey to build it will not be given until about 1991-92.

It seems that the general feeling in Europe is that the JET facility at Culham is the largest physics device that it is sensible to build, and that the NET must have, as an important part of its research program, the obtaining of engineering test data and technology base information. Dr. Toschi apparently feels that it is very important to begin the acquisition of technology related information, and that such a research program should start right now, or as soon as possible. Dr. Toschi feels that it is going to be a difficult job not to go too far beyond the physics data base of the JET experiment, while at the same time designing a quasi-steady state burning plasma experiment that will be sufficiently in advance of the JET facility to justify its very large cost of construction.

He said they have a small group looking at compact tokamak reactors and other similar alternates, but at present he does not see compact reactors, even high-field, compact DT tokamak reactors, as a viable alternative to a large DT tokamak. When I expressed suprise at this, considering his background as director of the Frascatti lab, where a high field, compact tokamak experiment has been one of their principal programs, he commented that this experience of his was sufficent to convince him that compact reactor concepts are not yet reliable enough and with the physics data base required for the NET-generation of reactors. He intended to rely heavily on the consensus information developed for the INTOR study, as a first approximation to the NET design.

Dr. Toschi but several questions to me about the politics of the US Fusion program, and the likely development of the US fusion program beyond the TFTR. He was particularly interested in the role of the electric utilities in fusion energy development, and commented that in Europe there was virtually no electric utility involvement in the fusion program, even though in most European countries fusion research and the electric utilities were both basically government-supported enterprises. Dr. Toschi must have found our conversation interesting, since it went an hour and a half beyond the originally scheduled half hour duration.

Also at Garching, I had an opportunity to talk with Dr. Aldo Nocentini, of the NET team, whose area of interest is the scaling of tokamaks. He was interested in some of my past scaling law studies, and I had a conversation with him which confirmed my previous impression that the uncertainties in scaling tokamaks from their present sizes to the scale of NET, or a demonstration reactor, are enormous, and the risks very great. The coefficients for the confinement time scaling of tokamaks with auxiliary heating change on almost a monthly basis, and even the functional dependence on the various machine and plasma parameters appear to change. The only reasonably constant factor in this shifting picture is the neo-Alcator scaling law for confinement in ohmically heated tokamaks. This appears to be an upper limit for the other scaling laws, which have been observed when auxiliary heating is brought into play.

I had a very interesting conversation with Dr. J. Nuehrenberg, who is head of a theoretical section responsible for stellarator confinement theory. He and his staff at Garching are in contact with their ORNL opposite numbers, who are involved with ATF (Advanced Toroidal Facility). All of the individuals with whom I spoke at Garching in the stellarator area were very familiar with developments at ORNL on the ATF. At least within West Germany and the Institute for Plasma Physics at Garching, the stellarator is regarded as a backup to the mainline tokamak confinement concept, almost in the same way that the tandem mirror is regarded in the United States. Dr. Nuehrenberg and his colleagues are well aware that the beta limit of classical stellarators is far too low for a practical reactor, and also that the magnetic field winding configuration is too complicated from an engineering point of view.

Dr. Nuehrenberg has been involved in the theory of the Wendelstein 7-AS (Advanced Stellarator) which is now being built at Garching, and he has also examined the equilibrium, stability, and drift surface confinement not only of the Wendelstein 7-AS, but other candidate stellarator like devices including the heliac, modular torsatron, and similar devices. he remarked that because fluctuation induced transport was likely to be a more important radial loss mechanism in stellarators than in tokamaks, as a result of the

stellarator escape cone, which is nearly perpendicular to the magnetic field lines in velocity space, and is not present in tokamaks.

I spent a very interesting three hours in the afternoon with Dr. H. Wobig, a group leader of the Wendelstein 7-AS team. We discussed many aspects of stellarator and torsatron physics, including their attempts to design and build the next generation beyond the Wendelstein 7-AS, a much larger device which would have enough clearance behind the confinement volume for a relatively thick blanket. One of the problems with the Wendelstein 7-AS design, is that the particle drift surfaces come relatively close to the vacuum wall (this was also a problem with the ATF design at Oak Ridge), but they have formulated or discovered some more advanced magnetic winding configurations which will allow enough clearance between the confinement volume and the first wall or the coils for a blanket. Dr. Wobig escorted me to an experimental bay where they have set up the first prototype models of the Wendelstein 7-AS coils and vacuum system. I was astonished at the large dimensions of the Wendelstein- 7 AS experiment. It will surely be the largest stellerator-like experiment in the world, about the same dimensions, roughly, as the Heliotron-E experiment at Kyoto, Japan. The vacuum vessel for the Wendelstein-7 AS is certainly the most complicated piece of stainless steel fabrication technology that I have ever seen. The cross section of the confinement volume is roughly oval-shaped and this oval rotates around the magnetic axis as one moves around the major circumference of the torus. In order to compensate for this rotating oval, and allow diagnostic access between the coil windings, the vacuum vessel (made out of eight millimeter thick stainless steel) had to be formed into a very complicated shape. Dr. Wobig worked with the Swiss fabrication company that made the sector which he showed me. The manufacturer is now in the process of fabricating the rest of the vacuum vessel. The coils required for the Wendelstein -7-AS are probably the most complex geometrically of any normally-cooled copper coils used in fusion experiments to date. According to Dr. Wobig, they had to have a special development program to find flexible conductors that could be wound into the complicated individual coil modules, without springing back when the tension was released from the coil after winding. These problems have

been overcome, and the complex modular coils required for the Wendelstein-7-AS are now being fabricated.

While I was there Dr. Wobig also showed me the Wendelstein -7-A experiment which is a classical, l = 2 tokamak which is still operating at Garching, and is scheduled to be shut down in 6 months to a year for the assembly of the Wendelstein - 7-AS. The Wendelstein-7A experimental results were described in an invited paper on this machine at the Lausanne conference. These results have been very encouraging, having achieved, with energetic neutral injection, values of the plasma stability index beta that are those predicted theoretically (a few percent), while achieving number densities up to 10^{14} particles per cubic centimeter. Another very large experiment is at Garching is the ASDEX, or (Axi Symmetric Divertor Experiment) which is a tokamak with a large divertor which can be operated without any limiter in the immediate vicinity of the plasma. The absence of a limiter or scrapeoff device apparently makes it possible to get impurity levels on Asdex down to relatively low levels, while raising the electron temperature at the edge of the plasma much higher than is possible with limiter-based plasmas. The principal achievement of the Asdex experiment so far is that when they operate with the divertor on, they can achieve a so called "H-mode" of confinement, in which the scaling of confinement time approaches that of the neo-Alcator scaling law.

I have the annual report of the Institute for Plasma Physics for 1983 in my office. It is written in English, and is available to anyone who wishes more information about the research program at Garching.

<u>Visit to the Culham Laboratory JET Site, Friday, July 6, 1984</u>

I made arrangements with Dr. John Butterworth of the fusion technology group at Culham to visit his group, the Cleo experiment at Culham, and the JET site. I had a very interesting visit to the JET site, during which Dr. John Maples escorted me around and showed me the very impressive JET tokamak. When I visited this site two years ago, the JET facility was just being assembled; one year ago it achieved its first plasma, and is now in routine operation up to a total plasma current of three megamps. They hope to apply neutral beam heating on JET for the first time sometime

in early 1985, and ICRH heating power sometime later in 1985. The JET apparatus itself was not accessible to visitors when I was there, since it was undergoing discharge cleaning. I did see the neutral beam test facility, which is currently set up in the "hot cell"; the diagnostics hall; and the assembly hall, where they were making ready some neutral beam injectors and additional diagnostics for installation on JET. The recent experimental results of the JET experiment were summarized in Allen Gibson's invited talk which I described above. The scale of the JET facility is impressive and the engineering of the entire facility and its auxiliary office and operational buildings is absolutely first class, far more impressive than our own TFTR experiment.

They apparently have not changed their intention to burn deuterium and tritium only after a very long series of preliminary trial experiments with ordinary hydrogen; these DT experiments are not anticipated before about 1989, inspite of pressure on them from the TFTR experiment, which intends to burn DT rather early in its operational history. I found the diagnostics hall particularly impressive, since all of the diagnostic equipment is outside the shielding wall which will be needed for DT operation. They are developing the technologies needed for remote diagnosis of burning tokamak plasmas and seem to be well ahead of us in this respect. Many of the RF-based diagnostics were being set up and debugged when I was there It was evident that the technology required for these diagnostic instruments have been fabricated by companies and national laboratories from all over Europe.

I had some interesting talks with several members of the Cleo group, about their recent series of comparisons in which they operated the Cleo device as a tokamak; a stellarator; a helically-assisted tokamak; a reversed field pinch (RFP); and as an OHTE (Ohmically Heated Toroidal Experiment). The Cleo device is one of the few that was designed with toroidal magnetic fields and helical windings sufficient for operating in these various containment modes; by adjusting the machine parameters they are able to go smoothly from one mode of operation to another, and to make comparative studies of confinement lifetimes, number densities, beta limits, etc. in the same machine and with the same diagnostics. They have found thus far for example, that confinement has been best in stellarators, but the beta limits

highest in their tokamak configuration. Because they have difficulty in varying the number density as an independent parameter, they have not yet been able to determine the scaling laws for confinement in configurations other than the conventional tokamak; they hope to get scaling information from the other configurations in the near future.

I gave a seminar at Culham on some of our work here at the UTK Plasma Science Laboratory, which seemed to be well received, and resulted in several requests for reprints, in addition to distribution of all of the reprints that I had brought along. The fusion technology effort at Culham is a rather small one, involving only about 6 or 8 professionals; they do not seem to be well integrated into either the experimental program at Culham, or into the NET or JET programs. I got the rather clear impression that the physicists are still very much in charge of the European fusion program and, except for Dr. Toschi of the NET team, the importance of engineering test data for the future of fusion energy does not seem to be widely appreciated there.

APPENDIX D

UNITED STATES AIR FORCE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BUILDING 410, BOLLING AFB, D. C. 20332

GRANT NO.	EFFECTIVE DATE	PURCHASE REQUEST NO.	PROJECT-TASK	PAGE 1 OF 3
AFOSR-85-0152	15 Feb 85	FQ8671-8500298	2917/A6	

GRANTEE
University of Tennessee
404 Andy Holt Tower
Knoxville TN 37916

AUTHORITY
10 U.S.C. 2358

AMOUNT
$233,745

DURATION (Months)
12

PRINCIPAL INVESTIGATOR
Dr. J. Reece Roth

ADMINISTRATIVE OFFICE	SPONSORING SCIENTIFIC OFFICE	PAYING OFFICE
AFOSR/PKZ Building 410 Bolling AFB DC 20332-6448	AFOSR/NP Building 410 Bolling AFB DC 20332-6448	Det 1, 76 ALD/ACFMCC Bolling AFB DC 20332-5260

NEGOTIATOR (Name, Organization, Telephone No.)	PROGRAM MANAGER (Name, Organization, Telephone No.)
JANE D. DADE PKZ (202) 767-4951/jdd	Dr. Robert J. Barker NP (202) 767-5011

RESEARCH TITLE
"Investigation of RF Emissions from Two Beams Interacting with an Electric Field Dominated Plasma"

ACCOUNTING AND APPROPRIATION DATA

575 3600 295 47B1 612917 A6 00000 61102F 503700 F03700 AJZ $233,745

PAYMENT SCHEDULE

$233,745 on or after 15 February 1985

TERMS AND CONDITIONS

THIS GRANT IS ISSUED UNDER THE DEPARTMENT OF DEFENSE (DOD) - UNIVERSITY RESEARCH INSTRUMENTATION PROGRAM (FY 1984/FY 1985) FOR THE PURPOSE OF UPGRADING THE UNIVERSITY RESEARCH INSTRUMENTATION IN ORDER TO IMPROVE THE CAPABILITY OF UNIVERSITIES TO PERFORM RESEARCH IN SUPPORT OF NATIONAL DEFENSE. SPECIFICALLY IT IS A PROGRAM OF SUPPORT FOR THE ACQUISITION OF RESEARCH EQUIPMENT FOR THE STIMULATION AND SUPPORT OF BASIC RESEARCH UNDERLYING THE TECHNOLOGY GOALS OF DOD.The above funding is hereby granted by the Air Force Office of Scientific Research (AFOSR) for the acquisition of equipment identified in the equipment list contained herein. No indirect costs are chargeable to grant funds.

Pursuant to the provision entitled "Cost Sharing" of the AFOSR Brochure entitled "Administration of U.S. Air Force Grants and Cooperative Agreements for Basic Research, August 1983" the Grant amount is $233,745 and the Grantee cost sharing amount is $0 (The total project cost is $233,745).

PRINCIPLE INVESTIGATOR

FOR THE GRANTEE		FOR THE UNITED STATES OF AMERICA	
SIGNATURE OF PERSON AUTHORIZED TO SIGN		SIGNATURE OF CONTRACTING OFFICER	
NAME AND TITLE OF SIGNER (Type or Print)	DATE SIGNED	NAME OF CONTRACTING OFFICER (Type or Print)	DATE SIGNED
EMERSON H. FLY VICE PRESIDENT	MAR -1 '85	HARRY R. HARALDSEN	20 Mar 85

AFSC FORM JUL 84 442 PREVIOUS EDITIONS ARE OBSOLETE. AFSC-Andrews AFB DC 1984

Grantee is authorized to acquire the following items of permanent equipment listed below. Title to items shall vest in the Grantee at the time of acquisition and the Grantee agrees that no charge will be made to the Government for any depreciation, amortization or use charge with respect to such items under any existing or future Government grant or contract. Variation from these items require the prior written permission of the Contracting Officer.

Item Description	Estimated Charge To Grant Funds
Spectrum Analyzer Plug-In	$ 10,920
Automatic Preselector	5,980
Waveguide Harmonic Mixer Set	3,100
Histogramming Data Memory	990
Programmable 3-Speed Clock	1,170
Quad 10 Bit Transient Recorder	3,990
Memory 8210	590
Oscilliscope Camera	1,315
Mass Spectrometer	12,087
Magnet System and Power Supplies	25,000
Network Analyzer, Low Frequency	31,158
Controller and Accessories	19,653
Experimentation Accessories	1,420
Network Analyzer, High Frequency	86,598
Sweeper	26,630
Shipping	3,144

At any time during the performance of the research period, including at the completion of the research, the Grantee shall inform the Contracting Officer in writing of any grant funds in excess of the amount actually needed for the acquisition of the equipment specified in the grant. Disposition of such excess funds will be as determined by the Contracting Officer.

The following provisions of the AFOSR Brochure are incorporated by reference and made a part of this agreement:

COST SHARING ADJUSTMENT
EXPENDITURE LIMITATIONS
SUSPENSION AND TERMINATION
COST SHARING
FINANCIAL STATUS REPORTS
UNEXPENDED FUNDS AND EARNED INTEREST
MANAGEMENT SYSTEMS, ACCOUNTING RECORDS AND AUDIT
PROPERTY MANAGEMENT
EQUAL EMPLOYMENT OPPORTUNITY
PROCUREMENT STANDARDS FOR SECONDARY AGREEMENTS

Cost provided under this grant are exclusively for the acquisition of equipment and not for any salary costs for research. Indirect costs and costs for supplies, continuing operations and maintenance are not chargeable to grant funds. Other costs directly related to the acquisition of the equipment may be allowable as determined by the Contracting Officer.

Grantee will provide an interim status report 6 months from the award of the Grant and a final report sixty (60) days after completion of the Grant which will identify the equipment actually acquired (although it might vary with that described in the Grant) by name, manufacturer where possible, and cost described any special circumstances regarding the acquisition or changes to the equipment list. The final report will also include a concise summary of the research projects on which the equipment has been or will be used, including support of (a) the research work described in the proposal and (b) other research work of interest to the DOD. The AFOSR Program Manager may request up to two informal letter reports during the performance period which describe the Grantee's progress in acquisition or fabrication and use of the research equipment.

APPENDIX E

MICROWAVE SCATTERING AS A PLASMA DIAGNOSTIC

IN A PENNING DISCHARGE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Larry R. Baylor

June 1984

ABSTRACT

A microwave scattering apparatus consisting of 32.175-GHz Gunn diode in a conventional homodyne mixer configuation has been built to investigate plasma turbulence in a steady-state classical Penning discharge. The microwaves are incident on the plasma in the ordinary mode at a power level of 25 mW. The scattered microwave power is observed for scattering angles from 20 to 160° in a plane normal to the magnetic field axis. The scattered microwaves are fed to a balanced mixer where they are detected with crystal detectors. The detected signal is then displayed on a spectrum analyzer or fed into an analog-to-digital data handling system for analysis and correlation with other signals.

In these experiments the electron number densities ranged from 10^8 to $10^{10}/cm^3$, the magnetic field ranged from 0.1 to 0.4 T, the discharge current ranged up to 0.2 A, and the input power ranged from 50 to 400 W. The frequency spectrum, angular dependence, and scattering amplitudes were measured with the microwave scattering diagnostic. Data from the microwave scattering diagnostic were correlated with plasma operating conditions and with data from capacitive probes which measured electrostatic turbulence. The data indicate strong, low-frequency electrostatic turbulence in the plasma, caused by $E \times B$ drift.

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APPENDIX F

COMPUTER-AIDED REDUCTION OF PLASMA DATA

A Thesis

Presented for the

Master of Engineering

Degree

The University of Tennessee, Knoxville

Saeid Shariati

March 1985

ABSTRACT

Poor signal-to-noise ratios and the nonlinear characteristics of the data obtained by most plasma diagnostic equipment makes computer-aided data handling a desirable feature in plasma laboratories. The Lecroy 3500-SA32 signal analyzer is used as the data handling system in this work. The performance of the Lecroy 3500-SA32 signal analyzer, used for recording and reducing plasma data under the noisy environment of the laboratory, is reported. The data characteristics and software programs are discussed for three types of plasma diagnostic equipment: (1) Langmuir Probes; (2) Charge Exchange Neutral Energy Analyzers; (3) Retarding Potential Energy Analyzers. Three computer programs in FORTRAN 80 are included which obtain an iterated best fit of experimental data to the corresponding analytical expressions for each case. Plasma parameters such as ion kinetic temperature, electron kinetic temperature, electron number density, plasma potential, etc. are available on a real-time basis.

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